An Investigation of the Geotechnical properties of loess from Canterbury and Marlborough

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Abstract

Tunnel gully erosion is common in the loess deposits of the South Island of New Zealand. The loess deposits found on the Wither Hills (Marlborough) and Port Hills (Banks Peninsula) are prone to extensive tunnel gully erosion which has caused significant damage in both rural and urban areas. However, the loess deposits found on the Timaru Downs (South Canterbury) and the hills surrounding Akaroa (Banks Peninsula) are significantly less affected.

Geotechnical tests including pinhole erosion, uniaxial expansion, crumb test and dispersion % were carried out to determine the erosive and dispersive characteristics of loess samples from locations in the aforementioned areas. From this data, the extent to which geotechnical properties influence the incidence of tunnel gully erosion was determined. Other geotechnical characteristics such as grain size, clay mineralogy, exchangeable sodium content and insitu dry density were also evaluated in order to determine the controlling factors on the erosive and dispersive characteristics of the different loess samples.

In general, it was found that laboratory test results did not correlate fully with field erodibility. For instance, the two non tunnel gullied soils exhibited characteristics which suggested that they should be prone to tunnel gully erosion. The lack of correlation between laboratory test data and field erodibility suggests that other factors such as climate, land use and soil profile characteristics are important in determining the occurrence of sub-surface erosion.

A comparison was made of the loess stabilising properties of an enzyme based product known as Endurazyme and quicklime (CaO), a commonly used loess stabiliser. Tests were carried out on samples from the Timaru Downs and the Ahuriri quarry on Banks Peninsula. It was found that Endurazyme has a negligible effect on important geotechnical properties such as erodibility, dispersivity, durability, strength and maximum dry density/optimum moisture content.

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My family.

Contents

Chapter 1: Introduction

1.1 Background

Loess, an aeolian deposit composed mainly of silt sized particles blankets much of the hills and downlands of the South Island. Tunnel gully erosion and shallow mass movement in the Port Hills loess deposits have caused considerable problems for urban development. Much work has been carried out to determine the geotechnical properties of Port Hills loess, and as a result, land use planning based on detailed engineering geology site investigation is now commonly required. Also, the chemical stabilisation of loess (particularly using hydrated lime) is now regarded as a "normal" remedial measure in urban development on the Port Hills.

The loess deposits of the South Canterbury area are mostly non-erodible and stable, and for this reason, the geotechnical properties of South Canterbury loess are not well documented. The most extreme tunnel gully erosion in New Zealand occurs on the Wither Hills near Blenheim, although the geotechnical properties of Wither Hills loess have not been studied extensively because the impact of erosion is primarily in rural areas where soil conservation measures have been successfully implemented. The present study aims to compare geotechnical data of the loess deposits from South Canterbury, Banks Peninsula and the Wither Hills.

1.2 Project Objectives

The principal objectives of this project are:

1. To make a comparison of the geotechnical properties of loess deposits from six sites in the Canterbury/Malborough region (Fig.1.1). Emphasis has been placed on determining the erosive and dispersive properties of the soils, and the sites have been chosen so that they exhibit a wide range in susceptibility to tunnel gully erosion.

2. To determine the extent to which the erosive and dispersive properties of loess as

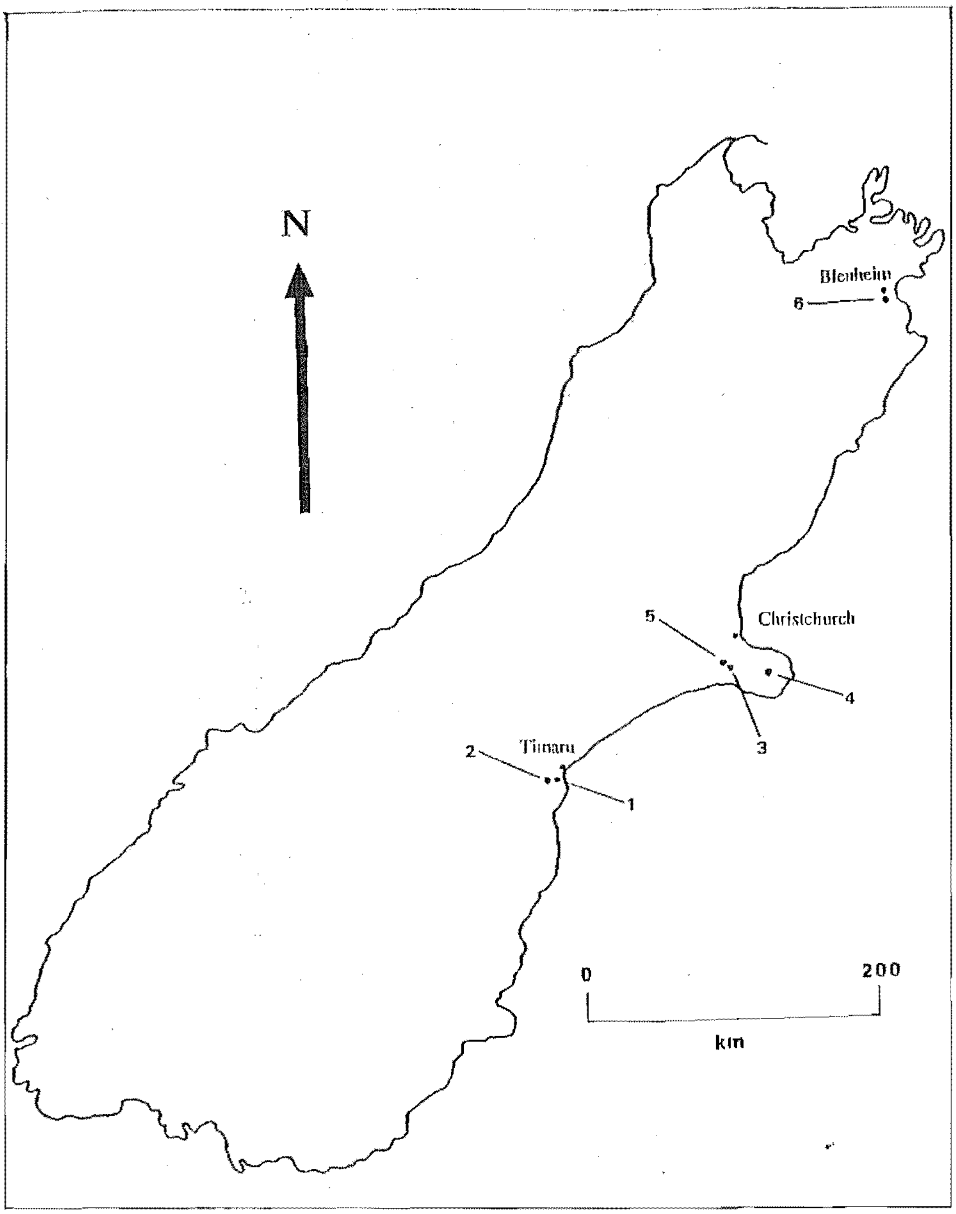


Figure 1.1: Site location map. 1 = Timaru Downs, 2 = Taiko, 3 = Gebbies Valley, 4 = Barrys Bay, 5 = Ahuriri, 6 = Wither Hills.

determined by laboratory testing correlate with the soil's susceptibility to tunnel gully erosion under field conditions.

3. To determine the extent to which a newly developed enzyme-based product known as "Endurazyme" stabilises loessial soils. Comparisons were also made with the quicklime stabilisation of loess.

1.3 The Loess Deposits of the South Island

1.3.1 Distribution

Loess is widely distributed throughout the South Island east of the Southern Alps. Loess more than 1 metre thick covers about 10% of the island, while soils with an identifiable loess content cover about 60% of the island (Bruce, 1972). Figure 1.2 shows the distribution of the major loess deposits in the South Island. The thickness of the loess varies greatly, but tends to be greater on lowland terraces and downlands than on hilly and steep lands (Bruce, 1972). On the Timaru Downs, Tonkin et. al. (1974) found the maximum loess thickness to be about 19 m, and Griffiths (1973) reports loess occurring up to 16 m thick on Banks Peninsula.

1.3.2 Origin

In an investigation of the loess deposits of the South Island, Raeside (1964) described loess as:

"...any fine textured deposit of aeolian origin other than sand dunes or tephra. It thus embraces all aeolian deposits where transport has been primarily by suspension, irrespective of content of organic matter, mineralogical composition, calcium carbonate content, degree of compaction or texture."

Like most of the world's loess deposits, the loess deposits of the South Island consist mainly of silt sized particles (2-60 microns). The silt was produced by glacial grinding processes in the Southern Alps during the Pleistocene glaciations, and probably also under freeze-thaw conditions. Initial transport by melt water streams was followed by deposition on fluvio-glacial outwash fan surfaces. Entrainment of the silt by the prevailing westerly winds was followed by redeposition on the flood plains and surrounding

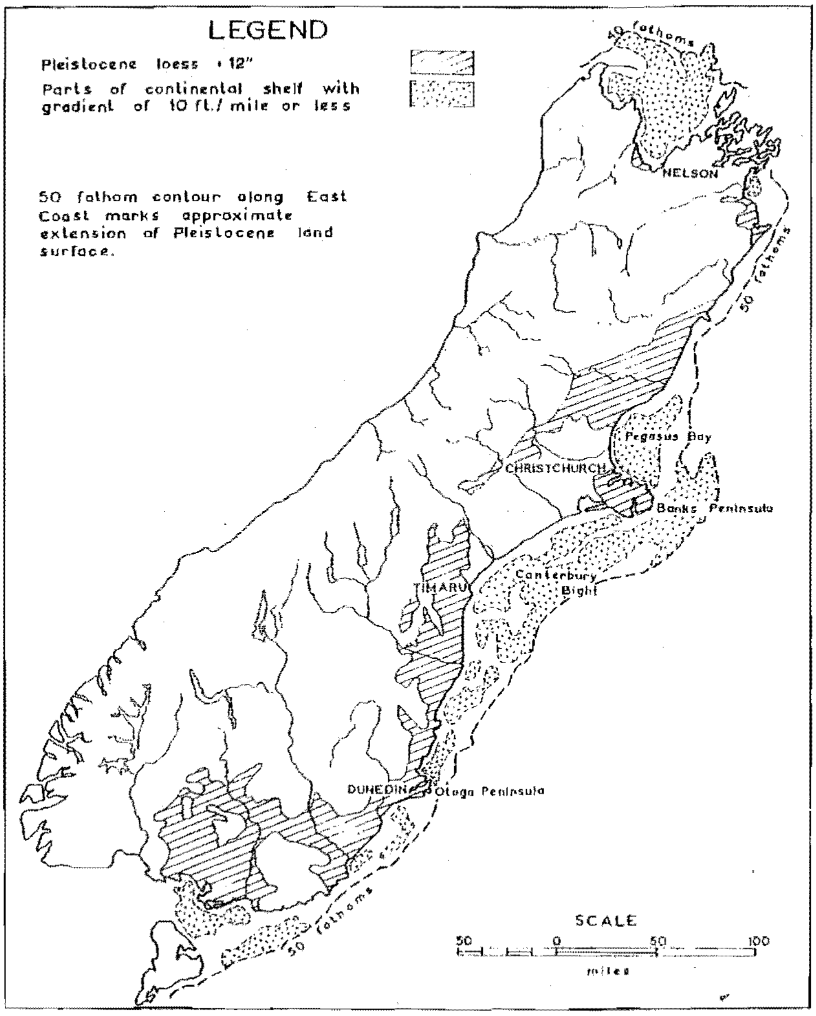


Figure 1.2: Distribution of the major loess deposits more than 30 cm thick in the South Island (after Raeside, 1964).

downlands. After deposition, many of the loess deposits were reworked by colluvial slope processes. From the time of deposition to the present day, erosion and soil formation processes continue to affect the loessial deposits (Bell and Trangmar, 1987). According to Raeside (1964), areas of continental shelf exposed at low stands of sea level during the Pleistocene also contributed fine-grained material which was deposited by easterly and southerly winds. The maritime influence, as evidenced by the occurrence of sponge spicules in the loess, extends some 50 km inland (Raeside, 1964).

Ives (1973) distinguishes between Post-glacial and Late Pleistocene Canterbury loess deposits. Post-glacial loess occurs adjacent to the major braided rivers and on the fan surfaces between these rivers. It is thickest on the south bank immediately adjacent to the river, and thins rapidly down-wind away from the river bank. The term "Late Pleistocene loess" embraces loess deposits which ceased to accumulate about 10 000 years ago. These deposits are found on the undulating to hilly land which fringes the Canterbury Plains on the south, west and north. The thickest Late Pleistocene loess deposits in Canterbury are found on the South Canterbury Downlands and on Banks Peninsula. According to Birrel and Packard (1953) Late Pleistocene loess has a higher clay content a lower porosity and is more weathered than Post-glacial loess.

1.3.3 Composition

South Island loess consists mainly of silt (65-80%), with minor amounts of clay (< 30%) and sand (< 20%). Quartz (50-60%) and feldspar (20-30%) are the dominant minerals of the silt and sand fractions. Accessory minerals such as muscovite, epidote, chlorite and hornblende are present in varying amounts depending on the composition of the source rock (Young, 1964; Raeside, 1964). According to Raeside (1964), the loess deposits of the South Island were derived from:

1. Southern Alps greywacke in Malborough, Canterbury and north-east Otago.
2. Metamorphic schists in Otago.
3. Tuffaceous greywackes, basic igneous rocks and schists in Southland.

Within each of the above classes, there are slight variations in composition from place to place depending on the presence of loess derived from local rocks, as well as variations in wind and air currents which affect transport, source region, and sorting during transport

(Bruce, 1972). Colluvial input from local sources also has an affect on composition.

Illite, interstratified illite/vermiculite, and to a lesser extent vermiculite, have been identified as the principal clay minerals in the loess deposits of the South Island. (Miller, 1971; Laffan 1973; Mackwell, 1986). According to Trangmar (in prep.) the presence of illite and interstratified illite/vermiculite reflects a low degree of soil weathering. Small amounts (5-15%) of Kaolinite have been identified in Banks Peninsula loess (Mackwell, 1986; Miller, 1971; Evans and Bell, 1981), and this is considered by Trangmar (in prep.) to originate from weathered volcanic rock materials which were incorporated into the loess as a result of slope movement processes.

1.3.4 Geotechnical Properties

Tunnel gully erosion and slide-avalanche-flow shallow mass movements have caused considerable problems for urban development on the Port Hills and other parts of Banks Peninsula. The presence of clay minerals with high exchangeable sodium percentages and susceptibility to slaking as a result of low cohesion were given by Bell and Trangmar (1987) as important geotechnical factors causing Port Hills loess to be prone to tunnel gully erosion. As a result, many authors have studied the geotechnical properties of Port Hills loess. Table 1.1 is a summary of the geotechnical properties of Banks Peninsula loess. Evans and Bell (1981) developed a geotechnical model of loess instability which enabled the design of engineering and remedial works on the Port Hills (Fig. 1.3). However, comparatively little geotechnical work has been carried out on the other South Island loess deposits.

Table 1.1: Geotechnical Properties of Banks Peninsula Loess

(Modified after Yetton (1986) and Goldwater (1990)

Parameter	Typical Range of Values	Reference
Porosity	30 - 40 %	Birrel and Packard (1953)
Void Ratio	0.4 - 0.7	Birrel and Packard (1953) Miller (1971)
Atterberg Limits	LL: 18 - 33 PL: 17 - 22 PI < 12 Activity: 0.1 (C horizon)	Crampton (1985) Yetton (1986) Alley (1966) Trangmar (in prep.)
Grain Size	Sand ≈ 10% Silt: 65 - 80%, Clay 11 - 25%	Alley (1966) Crampton (1985) Yetton (1986)
Dry Density	B horizon average = 1.54 t/m^3 Cx horizon average = 1.64 t/m^3) (1.51 - 1.88 t/m^3 range) C horizon average = 1.55 t/m^3) (1.32 - 1.7 t/m^3 range)	Evans (1977) Crampton (1985) Yetton (1986)
Linear Shrinkage	0 - 1%	Alley (1966)
Permeability	1.5×10^{-7} m/s (undisturbed) $\approx 1 \times 10^{-7}$ m/s (in situ test) 2×10^{-8} m/s (remoulded)	Birrel and Packard (1953) Sanders (1986) Tehrani (1988)
Internal Angle of Friction	≈ 30° (Peak, direct shear: drained)	Goldwater (1990)
Cohesion	0 - 20 kPa (Peak, direct shear: drained)	Goldwater (1990)
Total Dissolved Salts in Pore Water	1 me/100g (A horizon) to 60 me/100g (C horizon)	Miller (1971)
Exchangeable Sodium %	0.9 in B horizon to 41 deep in C horizon	Hughes (1970)
Quantitative Pinhole Erodibility Index (see Appendix G for explanation)	B horizon: 0.2 - 0.5 Cx horizon: 2.2 - 12.9 C horizon: 10 - 19	Schafer&Trangmar (1987) Trangmar (in prep.)
Dispersion (Crumb class)	B horizon: 2 - 4 Cx horizon: 2 - 3 C horizon: 2 - 4	Yetton (1986)

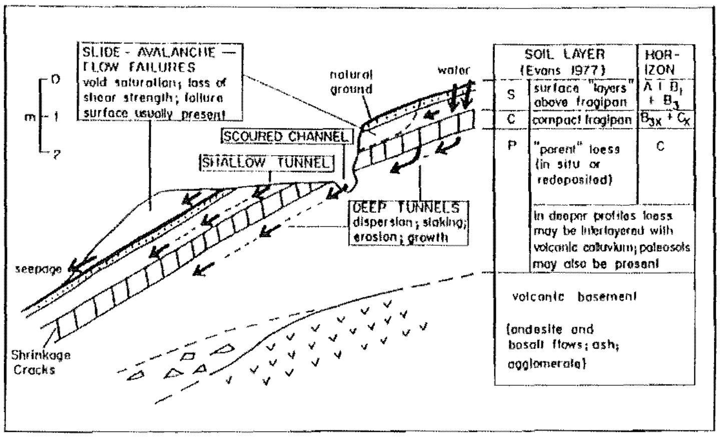


Figure 1.3: Geotechnical model for slope instability in Port Hills loess (after Evans and Bell, 1981).

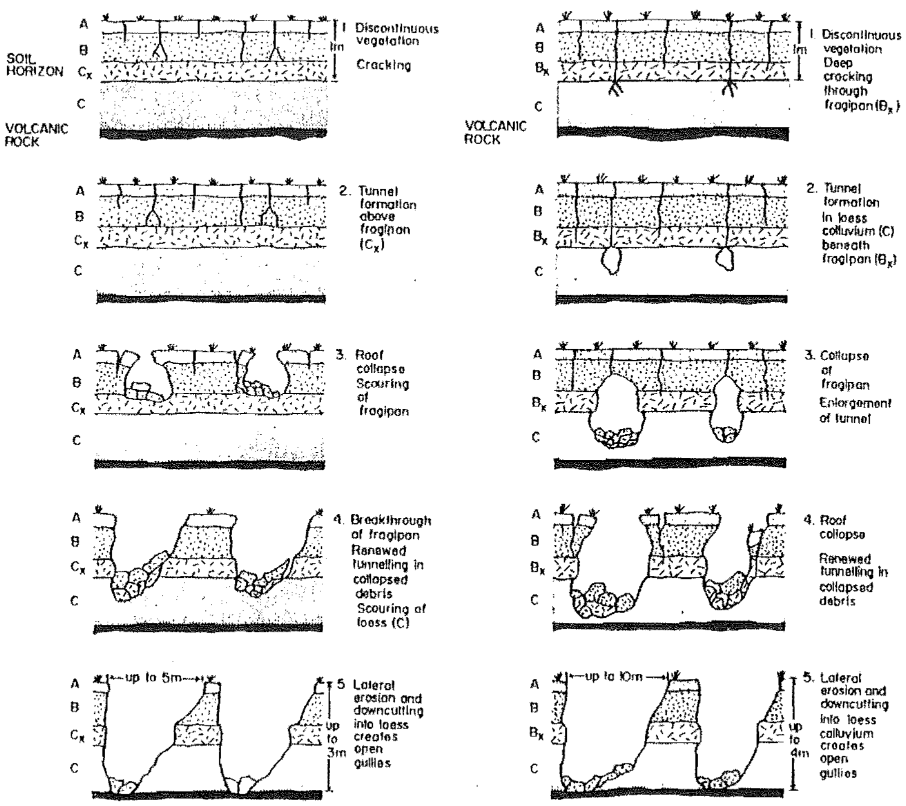


Figure 1.4: Models for the formation of (A) shallow and (B) deep tunnel-gully systems in Port Hills loess (after Bell and Trangmar, 1987).

1.3.5 Soil Profile Development

Most of the soils which have developed on the loess deposits covering the eastern downlands of the South Island belong to the yellow-grey earth soil group (Bruce, 1972). According to Lynn and Eyles, most (81%) of the tunnel gully erosion in the South Island occurs in soils of the yellow-grey earth group. Therefore an understanding of the properties of yellow-grey soils is vital in any study of tunnel gully erosion. Mclaren and Cameron (1993) describe Yellow-grey earth soils as:

"...weakly to moderately leached soils occupying subhumid moisture zones (500-1000 mm rainfall per annum) in which there is a summer moisture deficit and a winter moisture excess."

Yellow-grey earth soils occur in a large range of moisture conditions. This produces considerable variation in the morphological and chemical properties. As a result Yellow-grey earth soils are divided into three sub-groups depending on soil profile characteristics and moisture conditions; these sub-groups are described in Appendix B. The primary features of the Yellow-grey earth soils can be summarised as:

1. Grey to dark greyish brown silt loam topsoils with moderate amounts of organic matter (3-5%). They have moderately developed nut, granular, or crumb structure (see Appendix B for an explanation of soil science terminology used in this project).
2. The subsoil has a dense horizon (starting at a depth of 0.25 - 0.6 m) known as the fragipan which is regarded as the diagnostic feature of yellow-grey earth soils. The fragipan usually has a coarse prismatic structure with gammation (Appendix B) often occurring between the prisms. It was proposed by Raeside (1964) that the fragipan related to a past period of loess deposition. However, work carried out by Barrat (1981) showed that there was no evidence for a lithological break between the fragipan and the underlying parent material and it was concluded that the fragipan was of pedological origin. According to Trangmar (in prep.) the densification of the fragipan layer is produced by repeated expansion of weakly weathered illitic clay minerals under seasonally wet and dry conditions. These conditions are characteristic of the climate conditions in which most yellow-grey earth soils exist.

1.4 Tunnel Gully Erosion in South Island Soils

1.4.1 Terminology

Figure 1.4 shows that tunnel gully erosion is a compound erosion form which is initiated by subsurface erosion and often results in open gullying as a result of roof collapse. Therefore, depending on the extent of development, tunnel gully erosion may be expressed in three ways:

1. A tunnel in which no roof collapse has occurred.
2. A tunnel in which at least some of the tunnel roof has collapsed.
3. An open gully in which the tunnel roof has completely collapsed.

In this project, the terms: "tunnel", "partially collapsed tunnel", and "gully" are to be used to describe the three different stages of the tunnel gully erosion process given above. The term "subsurface erosion" is used as a general term to describe the process of soil erosion in a subsurface situation.

1.4.2 Mechanism

The tunnel gully erosion process in the South Island loess deposits may be summarised as follows (modified after Laffan and Cutler, 1977b; Hughes, 1972 and Bell and Trangmar, 1987):

1. Depletion of vegetation cover and hot, dry conditions promotes soil dessication. The resulting soil fissures extend to sub-surface soil layers, and subsequent seasonal wetting and drying causes the soil fissures to enlarge. The infiltration capacity of the topsoil is decreased by sun baking. As a result, the volume and velocity of surface run-off is increased.
2. The soil fissures allow infiltration of surface run-off. Subsoil void enlargement and interconnection caused by clay mineral dispersion and slaking mechanisms results in the formation of small tunnels.
3. Tunnel enlargement by erosion eventually leads to roof collapse.

According to Laffan and Cutler (1977b), the tunnel gully erosion on the Wither Hills initiates in the B_2 horizon (which occurs between depths of about 40 - 62 cm). Surface cracking was observed to extend into the B_2 horizon where many small cavities were also found.

According to Bell and Trangmar (1987), the tunnel gully erosion on the Port Hills initiates either above or below the fragipan (Fig. 1.4) which is regarded as being non dispersive and less permeable than the other layers as a result of increased density and soil chemistry. Tunnels form either above or below the fragipan depending on the extent to which the fragipan is affected by surface cracking. Wilms (1979) observed that tunnel gully erosion commonly occurred above the fragipan. This observation was contradictory to the results of pinhole tests that he carried out which showed that the fragipan was more erodible and dispersive than the overlying B horizon. The massive, dense structure of the fragipan was identified as being the major reason for the lack of tunnel gully erosion in the fragipan layer.

1.4.3 Distribution

Using data from the New Zealand Land Resource Inventory, Lynn and Eyles (1984) determined the distribution of tunnel gully erosion in New Zealand. They found that most of the tunnel gully erosion in the South Island occurs in the following areas: Northeast Malborough, Coastal North Canterbury, Banks Peninsula, North Otago downlands, Otago Peninsula and the mid Clutha valley (Fig. 1.5). Tunnel gully erosion affects 0.7% of the South Island and over 95% of the area affected by tunnel erosion is mantled by soils whose parent material is to some extent composed of loess. Hillsides with slopes of 21-25° are most prone to tunnel gully erosion (Figure 1.6); whilst tunnel gully erosion is very unusual on slopes of less than 7° and greater than 35°. Over 96% of recorded tunnel gully erosion affects grassland areas.

In a survey of the tunnel gully erosion on the Port Hills, Hughes (1972) found that slopes in the west to north quadrant, particularly those facing west to north-west, were most affected. The west to north facing slopes have greater exposure to both the afternoon sun and the hot, dry north-west winds; as a result soil dessication is more prevalent, and tunnel gully erosion is therefore more common. Yetton (1986) carried out a review of overseas research into sub-surface erosion in natural soils. He also found that the

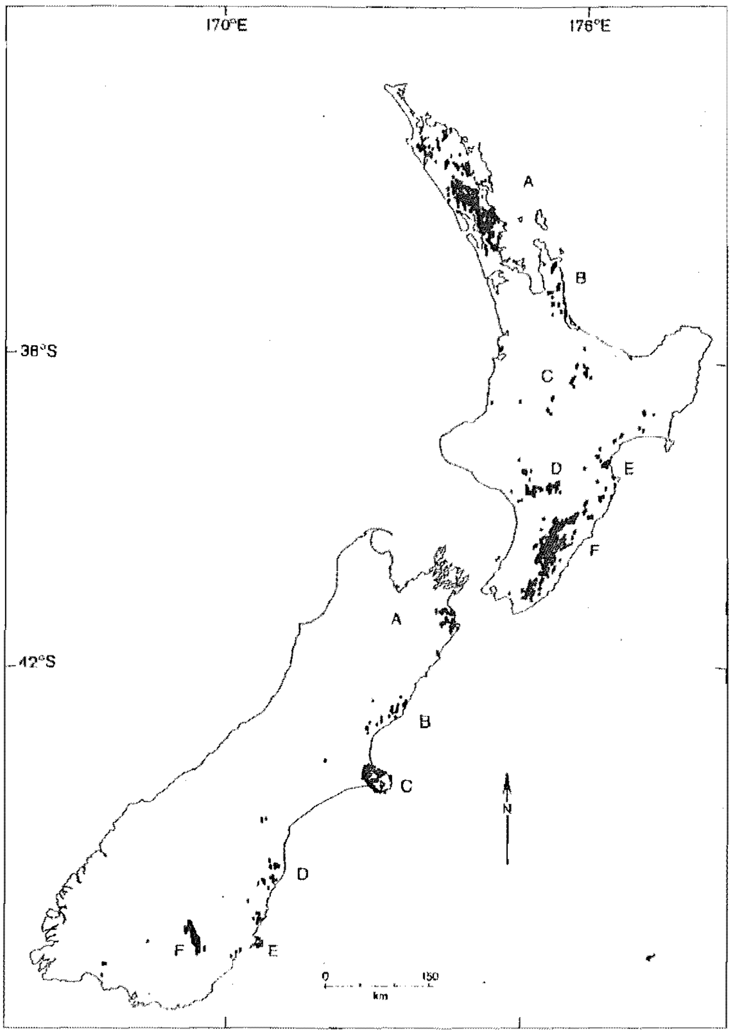


Figure 1.5: Distribution of tunnel gully erosion in New Zealand (after Lynn and Eyles, 1984).

dominant environment was arid and semi-arid grasslands, and that the most common erosion mechanism was by enlargement of dessication cracks.

1.4.4 Consequences

According to Trangmar and Cutler (1983), in terms of capital costs and amelioration, tunnel gullying and rapid mass movement are potentially the most serious erosion types on the Port Hills. The main consequences of tunnel erosion are listed below (modified after Trangmar and Cutler, 1983):

1. Loss of support for foundations.
2. Subsidence of lawns, gardens, paths, driveways etc.
3. Discharge of water and sediment into basements, gardens, storm water drains, streams etc.
4. Addition of water by tunnels to regoliths that are susceptible to mass movement. In a survey of shallow loess "soil slips" on Banks Peninsula, 14% of 181 slips on north facing slopes had tunnels in the head scarps (Pierson, 1983).
5. Pasture depletion by soil erosion.
6. Entrapment of wandering stock in partially collapsed tunnels.

Poorly designed engineering works in loessial soils on the Port Hills have often initiated or contributed to both surface (sheet and rill erosion) and sub surface erosion. Batters greater than about 1 m high may penetrate the fragipan layer, thereby creating a potential for tunnel gully formation in the underlying material. The installation of underground services by trenching and backfilling on sloping ground often results in seepage water concentration which causes subsurface erosion in either the loess backfill or in the surrounding in situ loess.

On the Wither Hills, severe tunnel gully erosion causes permanent loss of pastural productivity and also causes periodic flooding and sedimentation on valuable flat land at the base of the hills. Other adverse effects include increased difficulty in the control of weeds and rabbits, depressed land values and low aesthetic values.

1.4.5 Remedial Measures

The interception of surface or subsurface water before it enters tunnels or the interception of water which is in the cavity itself, has been found to be an effective, and relatively cheap way of preventing further tunnel gully erosion. This method has been used successfully by Yetton (1986) on various sites on the Port Hills. Figure 1.7 is an example of the use of a gravel filled trench to drain water that is flowing down a pre-existing tunnel.

The traditional method of stabilising tunnels as used by many local landowners has been the dumping of fill (e.g rock, building debris, tree cuttings and straw) into surface collapse holes. This method has been found to be ineffective, as tunnel throughflow is often concentrated around the edge of the fill, causing the fill to settle into the semi-liquid loess base. Piles that have been driven through to solid ground have been found to be an effective way of providing support for foundations that are threatened by subsidence (Yetton, 1986).

Chemical stabilisation methods which render dispersive loessial soils non erodible are now accepted as standard remedial measures in urban development on the Port Hills. Hydrated lime is the most commonly used chemical, although orthophosphoric acid (H_3PO_4) and quicklime (CaO) have also been used. Cavity excavation and backfilling with lime stabilised loess is the most common form of soil stabilisation on the Port Hills (Bell, Glassey and Yetton, 1986). In this method, the soil is excavated and pulverised, the stabiliser is then applied by mixing at or close to optimum moisture content. The stabilised soil is then recompacted to a predetermined depth and left to cure to allow the development of the desired soil properties. A second method of stabilisation utilising slurry or grout injection at depth has also been used. Evans and Bell (1981) used a slurry mix to infill tunnels which had formed along a mains water supply pipe. A mix of 5 cubic metres of loess, 2 cubic metres of sand and 50 litres of 81% phosphoric acid produced an erosion resistant slurry. Yetton (1986) used lime and cement-stabilised slurries mixed with sands and sandy gravels to fill a cavity resulting from sub surface erosion in undisturbed loess. The operation was successful and compared to excavation and recompaction, proved to be inexpensive.

The most successful treatment of severe tunnel-gully erosion on the Wither Hills (Blenheim) is the mechanical reshaping of hill slopes using an angle-bulldozing method to

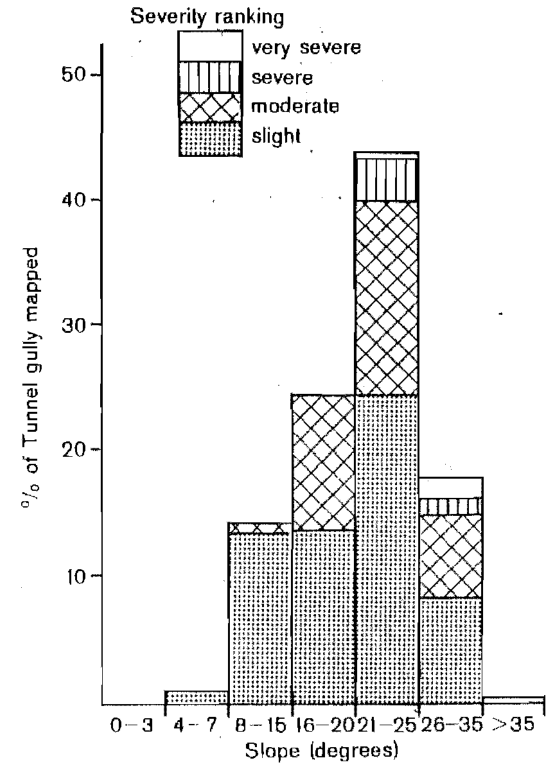


Figure 1.6: Relationship between slope angle, extent and magnitude of tunnel gully erosion (after Lynn and Eyles, 1984).

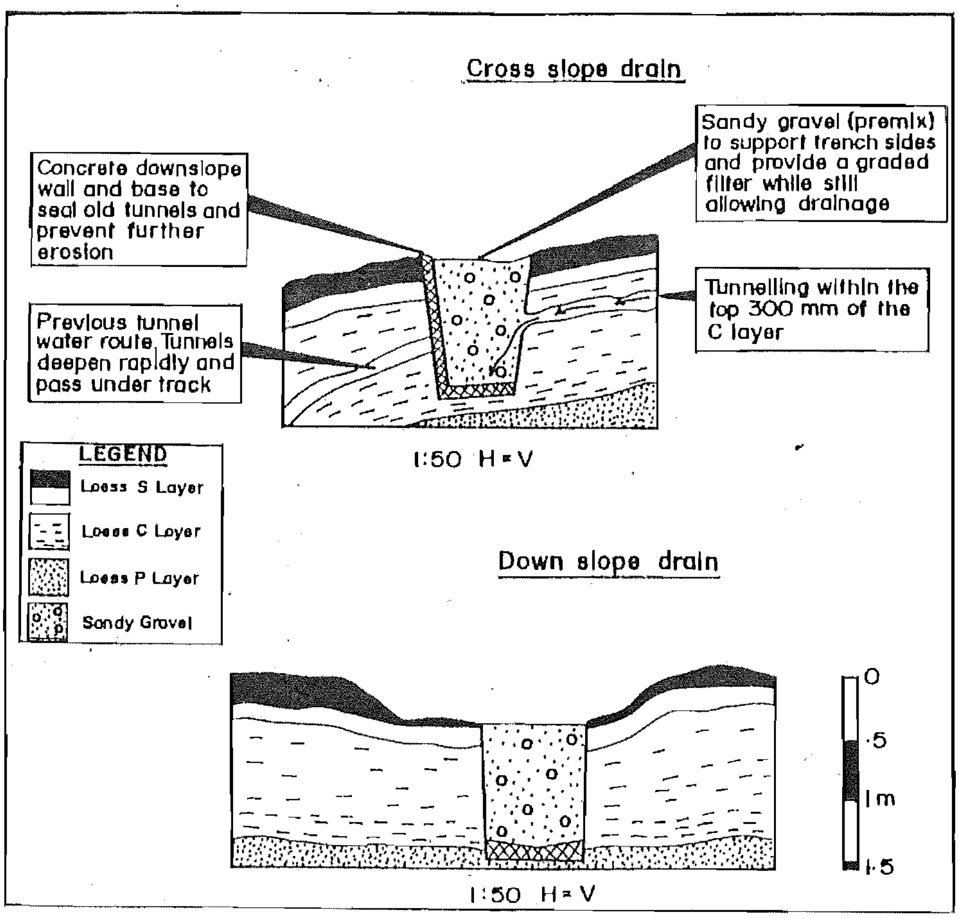


Figure 1.7: Tunnel interception drain (after Yetton, 1986).

erase all traces of the tunnel gullies, followed by sowing in order to turn the slope back to pasture (Laffan and Sutherland, 1988). Revegetation methods such as the planting of native grasses, pasture improvement by grazing management and plantation forestry have all been tried with relatively little success on the Wither Hills (Laffan and Sutherland, 1988). Sheppard and Lambrechtsen (1983) recommended four land management options: afforestation, agroforestry, pasture and amenity/recreation to restore land on the Port Hills affected by tunnel gully erosion or to prevent tunnel gully erosion.

1.5 Project Methodology

In order to achieve the objectives of this thesis, soil samples were collected from six sites which exhibited a range of susceptibility to tunnel gully erosion. Samples for stabilisation investigations were collected from the Ahuriri loess quarry and the Timaru Harbour Board quarry. Sampling and initial testing was carried out between April and September 1994. Soil samples were collected by the use of a hand auger and undisturbed soil tube samples were collected by the use of a sample tube driver (Appendix A). Soil profile information was determined from auger hole logs and exposed soil faces at or near to the site.

Laboratory testing was carried out in two distinct phases. During the first phase (which was carried out between May and December) tests were carried out to investigate the dispersive and erosive characteristics of loess from the six sites. During the second phase of testing, (which was carried out between January and March) tests were carried out on chemically stabilised samples. During the first phase of testing the following tests were carried out: pinhole test, crumb test, uniaxial expansion, grain size, dispersion %, atterberg limits, clay mineral cation concentration, and clay mineralogy. During the second phase of testing the following tests were carried out: shear strength, jar slake test, permeability, unconfined compressive strength, linear shrinkage, grain size, atterberg limits and uniaxial expansion. All laboratory testing (except for cation concentration) was carried out in the engineering geology, sedimentary and geochemistry laboratories in the Geology Department at the University of Canterbury. Cation concentration testing was done by outside contract.

1.6 Thesis Outline

Chapter One lists the project objectives and provides general information on tunnel gully erosion and the loess deposits of the South Island. Chapter Two is a review of the different test methods that have been used to determine the dispersive and erosive properties of loess. Background information is also given on the processes of clay mineral dispersion and slaking. Site descriptions are given in Chapter Three, with background information on geology, physiography, loess deposits and tunnel gully erosion. In Chapter four a comparison of the geotechnical results from the different sites is presented. Investigations will be carried out to determine the extent to which laboratory determined soil characteristics reflect the degree of field erodibility. The first part of Chapter five presents the results of an investigation into the possibility of using quicklime stabilised loess from the Ahuriri quarry as fill material for an earth dam proposed on the Port Hills, as part of a sub-division development scheme. In the second part, an investigation into the loess stabilising properties of Endurazyme is investigated. Chapter six is a summary of the findings of the previous chapters, with specific conclusions and recommendations.

Chapter 2: Review of Test Methods

2.1 Introduction

Slaking and clay mineral dispersion have been identified by various workers (e.g Hughes, 1970, Miller, 1971 and Laffan, 1973) as the main processes which cause some South Island loess deposits to be prone to tunnel gully erosion. In this chapter, a brief description of the mechanisms of slaking and clay mineral dispersion is given, along with a review of the different laboratory test methods which have been used to identify the susceptibility of different soils to sub-surface erosion.

2.2 Clay Mineral Dispersion

2.2.1 Mechanisms

Clay minerals are composed of sheets consisting of silicon, aluminium, magnesium and/or iron cations surrounded and held together by oxygen and hydroxyl groups. The cations in the layers can be replaced by ions of a smaller charge (e.g Al^{3+} for Si^{4+} or M^{2+} for Al^{3+}), resulting in a net negative charge. The negative charge is neutralised by low valency cations, the most common being Ca^{2+}, Mg^{2+}, Na^{+} and K^{+} (Mclaren and Cameron, 1993). The low valency cations reside between the clay mineral layers and they are not an integral part of the clay mineral structure. As a result, they can be replaced with various degrees of ease by other cations in the pore water surrounding the clay mineral. For this reason they are known as exchangeable cations.

The cation exchange capacity (CEC), expressed in me/100g (for definition, see Appendix B) is a measure of the soil's ability to hold exchangeable ions and is equal to the negative charge per unit mass of the soil. The exchangeable cations form a diffuse cloud known as the cation exchange complex (or double layer) around the clay particles. The proportion of Na^{+} ions in the cation exchange complex is indicated by the exchangeable sodium percentage (E.S.P) .The formula used to determine the E.S.P of a soil is:

$$E.S.P = 100 \times (Na^{+} \div C.E.C)$$

where **Na^{+}** is the concentration of sodium in the exchange complex expressed in me/100g and the **C.E.C** is the cation exchange capacity of the soil in me/100g.

Clay Mineral dispersion (or deflocculation) occurs when the repulsive forces (electrical surface forces) between individual clay particles exceed the attractive (Van der Waals) forces so that when the clay mass is in contact with water, individual clay particles are progressively detached from the surface and go into suspension. If the water is flowing, the dispersed particles are carried away (Elges, 1987).

Monovalent cations (e.g Na^{+} and K^{+}) are held less strongly to the clay mineral surface than ions of higher valences (e.g Ca^{2+} and Mg^{2+}), and as a result they cause the double layer to expand. The Na^{+} ion has the highest hydrated radius of the monovalent ions commonly found in the exchange complex, and is therefore the ion which causes the most expansion in the double layer. High ESP soils will have clay minerals which have expanded double layers with repulsive forces dominant. Because of this, the clay minerals will have a tendency to disperse (Mclaren and Cameron, 1993).

Clay mineral type also has an effect on dispersion. The Smectite clay mineral family (of which montmorillonite is a member) are most often associated with high levels of dispersion (Bell and Maud, 1994a; Sherard, 1972; Elges, 1985). Smectitic clay minerals have a very low amount of negative charge associated with each layer. Hence, very few inter-layer cations are required to balance the charge. As a result, the clay layers are loosely bound to each other. This causes larger inter-layer separations, higher cation exchange capacities, (Table 2.1) swelling and dispersion. Kaolinitic clay minerals have high negative layer charges and are usually not susceptible to dispersion (Bell and Maud 1994a). Illite and Vermiculite clay minerals have properties which are intermediate between Smectite and kaolinte.

Soil water content also has an affect on dispersivity. Soil drying causes clay minerals to shrink and as a result, clay mineral separations decrease. Once the clay particles are brought into very close proximity (less than 1Å), the attractive Van der Waals forces increase very rapidly. As a result of the increased Van der Waals forces, the clay particles become locked together and it becomes very hard to separate them again. Therefore, dry soils tend to be less dispersive than moist ones (Flanagan and Holmgren, 1977).

Organic soil matter (humus) reduces dispersivity. When the negatively charged and gel like humic material is adsorbed onto clay mineral surfaces, the properties of the clay mineral are changed. The adsorption of organic material on mineral surfaces and edges leads to interparticle bonding between the clay minerals which acts to reduce dispersion tendency (Mitchell, 1976).

According to Holmgren and Flanagan (1977) a high pH promotes dispersion Dispersive soils typically have pH values in the range of 6-8 Bell and Maud (1994b).

2.2.2 Test Methods

2.2.2.1 Crumb Test

The crumb test is a simple and quick way of determining dispersion. Basically, the crumb test involves the immersion of a crumb of soil at natural water content into a beaker of water. The extent of the colloidal cloud is noted and the sample is allotted a dispersion grade. The crumb test has been widely used, and it has been found to be especially useful as a field test to identify dispersive soils in borrow areas (e.g Cole et. al. 1977).

The crumb test was originally developed by Emerson (1967). Swelling, slaking and dispersion were the properties used by to differentiate between the eight classes in Emerson's classification scheme (Fig. 2.1). Loveday and Pye (1973) modified the original test so that dispersion was the only factor used for classification. This version of the test had a 16 fold classification scheme and it took up to 20 hours to complete. A much simplified test with a 4 fold classification scheme based purely on observations of dispersion was developed by Sherard et. al. (1976b). In this scheme, crumb grades 1 and 2 were considered to indicate slight to no dispersive reaction, while crumb grades 3 and 4 indicated that the soil was dispersive. Sherard et. al. found that the crumb test was a useful

Colloid	CEC me.%
humus	100-300+[1]
illite (hydrous mica)	10-40
vermiculites	100-200
smectites	60-150
pedogenic chlorite	10-30
kaolinite, halloysite	2-15
allophane, imogolite	30-150[1]
Fe and Al hydrous oxides	<1[1]

[1] varies greatly with pH

Table 2.1: Typical cation exchange capacity values of clay minerals (after Mclaren and Cameron, 1993)

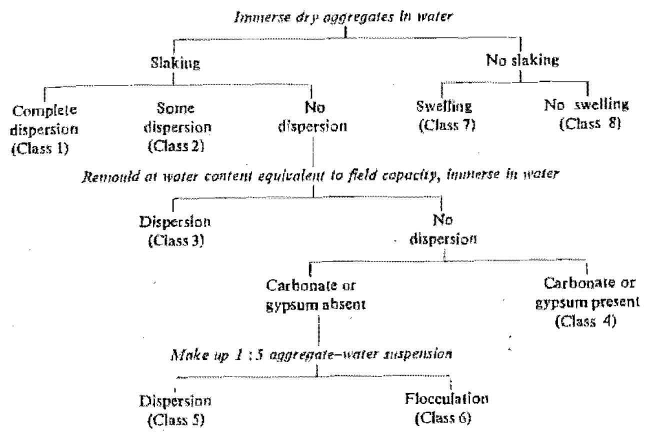


Figure 2.1: Scheme for determining the crumb class of a soil (after, Emerson, 1967).

indicator of dispersion in one direction only, i.e if the crumb test indicated dispersion, the soil was almost always identified as dispersive by other tests, however, many dispersive soils were found to be non-reactive in the crumb test. Sherards version of the crumb test is similar to the crumb test used in this project (see Appendix F.1).

Atkinson et. al. (1990) defined true cohesion as the component of shear stress available when a clay sample is affected by zero effective stress (i.e in still water). The cohesion can either be positive (i.e interparticle forces are attractive) or negative (i.e interparticle forces are repulsive), in which case the clay is dispersive. According to Atkinson et. al. the crumb test "has deficiencies" because the soil crumbs are usually not saturated and as a result, the extent of dispersion will be affected by internal suctions which produce "substantial" effective stresses. As a result of these suction forces, soils which are dispersive may give non dispersive results in the crumb test.

2.2.2.2 SCS Dispersion Tests

The Soil Conservation Services (SCS) laboratory dispersion test, also known as the double hydrometer test, was one of the first dispersion tests. The test was developed by G.M Volk in 1937 and has been used by the SCS for over 50 years. In the test, the amount of material finer than 5 microns (the clay fraction according to ASTM standards) is determined in the standard hydrometer grain size test. A parallel test is carried out in which no chemical dispersant is used in the water and in which the soil is not dispersed with strong chemical agitation. The clay percentage in the latter test is divided by the clay percentage in the first test to determine the dispersion %. A high dispersion % indicates that the soil is dispersive. According to Decker and Dunnigan (1977), the critical values for dispersion depends on soil type. The critical values which were based on the erosional performance of the soil in the field were found to be: > 25 for inorganic silts of low plasticity (ML) and silty clays (SC), > 35 for inorganic clay of low to medium plasticity (CL), and > 40 for inorganic clay of high plasticity (CH). However, based on results from flume erosion tests (section 2.4.2), Heinzen and Arulanandan (1977) found that the critical dispersion % values were 70 for CL and CH soils and greater than 50 for ML, SM, and SC soils.

In a review of the use of the SCS dispersion test, Decker and Dunnigan (1977) found that soil moisture content has a large affect on test results. Moist soils from flood retention dams in the Mississippi were found to have dispersion % in the range of 88 to

100%, while the same soil in the dry condition, had dispersion % in the range of 13 to 24%. It was also found that SCS test results were not always reproducible in the same laboratory.

Using samples of Port Hills loess, Schafer and Trangmar (1981) found a poor relationship between pinhole erodibility and dispersion as indicated by the pinhole test (Fig. 2.2). This poor relationship is due to the fact that clay mineral dispersion is only one of the factors involved in the erosion process of Port Hills loess.

2.2.2.3 Chemical Tests

Sherard (1972) devised a method of using sodium and total cation concentration in the cation exchange complex of clay minerals to predict dispersivity. This method is currently being used as a dispersion test in the ASTM (American society for testing and materials) standards. Figure 2.3 shows Sherards classification scheme in which pinhole tests (section 2.4.1) were used to define the three different dispersion categories. TDS is defined as the sum in me/l of the Na, K, Ca and Mg cations in the "saturation extract". The saturation extract is obtained from a "saturated soil paste" which is in theory in equilibrium with the cation exchange complex. Because the dispersion/cation chart was constructed using data from montmorillonite rich soils, Sherard (1972) made the assertion that the chart may only be applicable to soils rich in montmorillonite. According to Figure 2.3, soils at low TDS concentrations (less than 0.5 me/L) tend to be less dispersive than soils with higher TDS concentrations. This is opposite to what clay mineral dispersion theory suggests (see 1.4.1) and indicates a weakness in the scheme.

Craft and Acciardi (1984) carried out a statistical analysis to determine the degree of correlation between the cation data and the extent of dispersion (in the pinhole test) as predicted by Sherard's classification. It was found that only 60% of the soils were correctly classified. It was concluded that other variables besides pore water cations (e.g pH and water content) play important parts in the dispersion process and that Sherard's test was only reliable under certain soil conditions. Craft and Acciardi also had reservations about using the saturation extract as an indicator of cation concentration on the exchange complex.

In a study of Port Hills loess, Wilms (1979) found that dispersion predictions

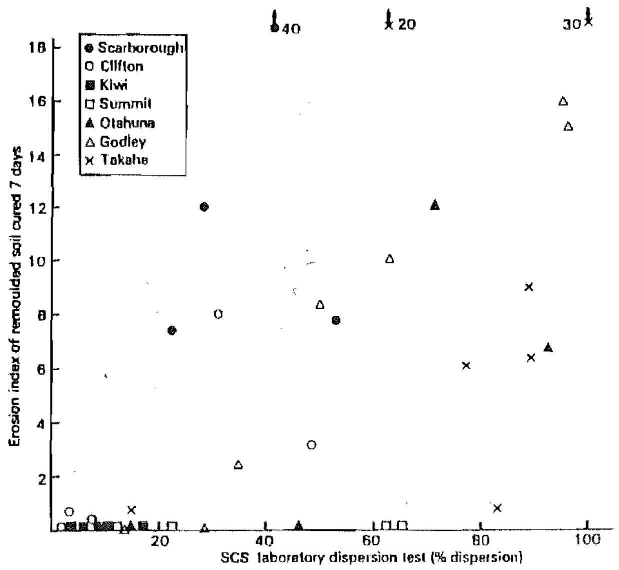


Figure 2.2: Comparison of SCS dispersion % with erodibility (after Schafer and Trangmar, 1981).

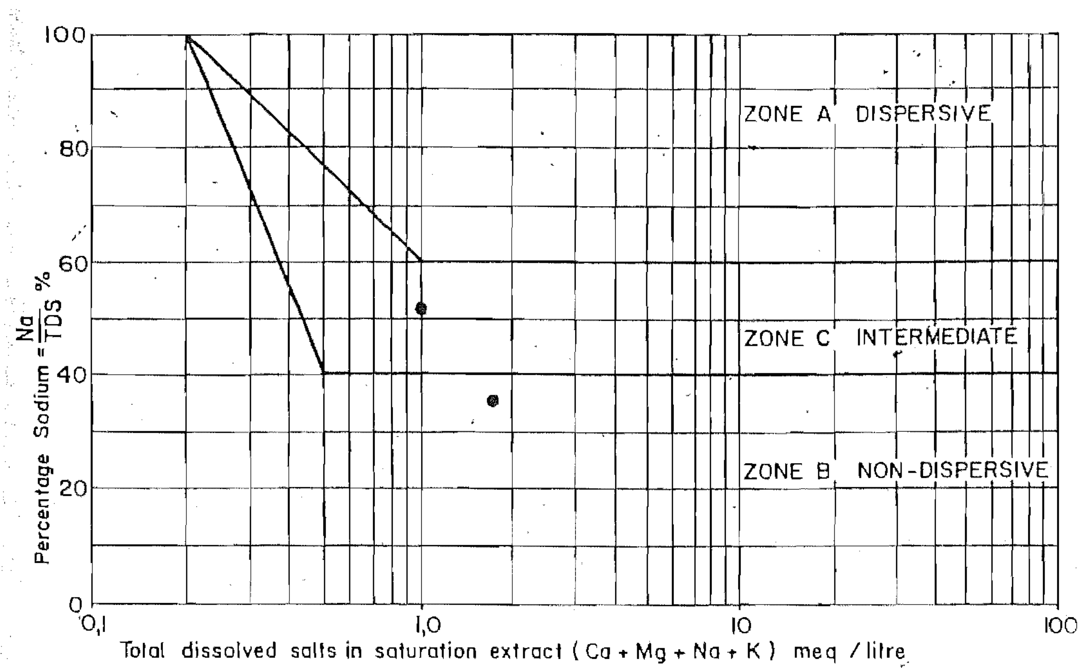


Figure 2.3: Chart for the determination of potential dispersivity based on % sodium and total cation content in the saturation extract (after Sherard, 1976a).

based on Sherards scheme were not in accordance field observations or pinhole test results. The results of the tests carried out by Wilms (Fig. 2.3), show that the two samples had cation contents which plotted in the intermediate and non dispersive zones even though the samples were from soils affected by tunnel gully erosion.

Exchangeable sodium percentage (the concentration of sodium on the cation exchange complex) has also been used to determine potential dispersivity. Different ESP values have been used to indicate potential soil dispersion, e.g: 10% (Elges, 1985); 6% (Crouch et. al. 1986); 8% (Emerson, 1960; Rallings 1966). Based on their findings from South African soils, Gerber and Harmse (1987) designed a procedure for identifying dispersive soils based on ESP and CEC. Bell and Maud (1994b) determined the ESP and CEC of known dispersive soils and found that they all plotted in the dispersive zone (Fig. 2.4) of Gerber and Harmses classification scheme. This result suggests that it is a promising method of determining potential dispersivity.

2.2.2.4 Cylinder Dispersion Test

Atkinson et. al. (1990) developed a test known as the "cylinder dispersion" test. This test was based on the idea that the main factor in assessing the dispersion potential of a soil is the "true cohesion" which is defined as the strength at zero cohesion. Essentially the test is an extension of the crumb test, the main difference being that suction forces are negated by ensuring that the sample is saturated. The test itself is relatively simple. A slurry (with a water content of approximately twice the liquid limit) is made. The slurry is then consolidated in a 200mm long, 38 mm diameter consolidation cylinder. When consolidation is complete, the sample will be approximately 80 mm long, and solid enough to be placed into a beaker of distilled water. Like the crumb test, the extent of dispersion is determined by visual observation. The cylinder dispersion test has only recently been developed and there are no other examples of the use of this test in practical situations.

2.3 Slaking

2.3.1 Mechanism

Slaking is the disruption and collapse of the soil structure during saturation by water. Hydration and deaeration are the primary mechanisms causing soil structure disruption. As the hydration front enters into the soil, air is trapped in the soil voids under positive pressure. The pressure acts to disrupt the structure of the soil (Holmgren and Flanagan, 1977). Emerson (1954) outlined the major factors affecting the degree of slaking as: rate of wetting, initial moisture content of soil, and the pore geometry of the soil voids. According to Moriwaki and Mitchell (1977), clay mineral dispersion and swelling also play an important role in the slaking process.

2.3.2 Test Methods

2.3.2.1 Soil Security Test

Tadanier and Ingles (1985) developed a test known as the "soil security test". They described it as "a simple test applicable to the evaluation of soils for water-retaining structures" which provides information on dispersivity, slaking and swelling (cracking). In this test a tube is used to take a core out of a sample compacted under standard conditions and in this way a soil cylinder is made. After weighing and measuring, each sample is tested by filling the central hole with water and recording the time taken for the cylinder to fail. The cylinder is considered to have failed when there is significant water loss into the tray in which the cylinder stands. The mode of failure is also recorded. From a relatively small amount of data a tentative conclusion was made that soils with failure times greater than 420 minutes could be accepted "without question" as suitable fill material for the construction of earth dams. The authors were also of the opinion that a soil with a failure time of greater than 45 minutes would be acceptable if compaction and water addition was strictly controlled. No published examples on use of the soil security test in the field could be found.

2.3.2.2 Uniaxial Expansion Test

Yetton (1986) developed the uniaxial expansion test (ISRM, 1981) to test the slakeability of Port Hills loess. In the test, a confined ring of soil is immersed in distilled water and the expansion in the vertical dimension is measured by a calibrated transducer. According to the results (Fig. 2.5), the expansion of Port Hills loess is the result volume increase resulting from slaking pressures rather than clay mineral expansion. Figure 2.5 shows that the plastic material (plasticity index = 13) had a considerably lower uniaxial expansion than the two non plastic samples. The high slaking resistance of the clay rich

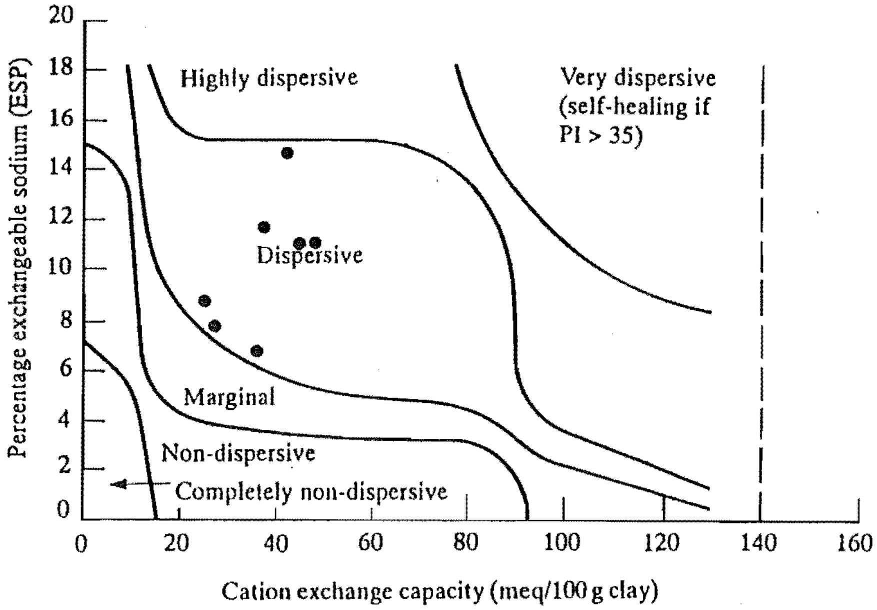


Figure 2.4: Prediction of dispersivity based on ESP and CEC (after Gerber and Harmse, 1987).

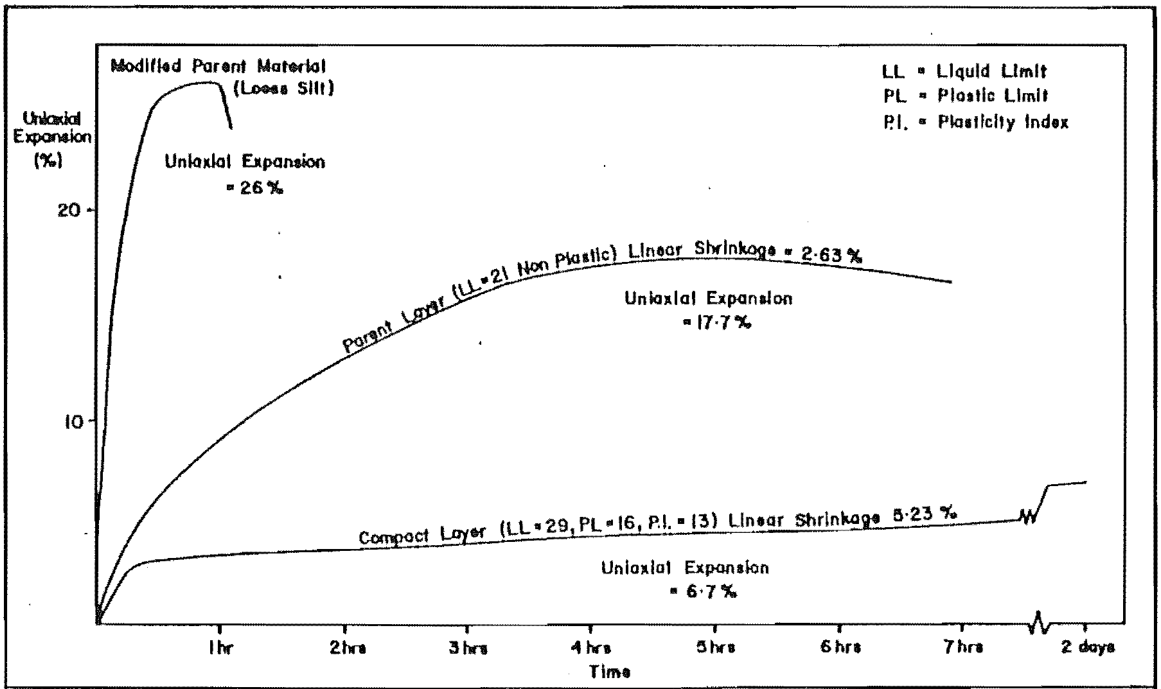


FIGURE 2.5: UNIAXIAL EXPANSION VERSUS TIME FOR TYPICAL COMPACT AND PARENT LAYER SAMPLES. NOTE ALSO THE SAMPLE OF SILT-RICH LOESS. ALL SAMPLES INITIALLY AIR DRY.

Figure 2.5: Uniaxial expansion versus time relationships for plastic and non plastic Port Hills loess (after Yetton, 1986).

soil was attributed to higher inter-particle bond strength as a result of the cohesive properties of clay minerals. The increased clay content would also reduce soil permeability hence reducing the rate and magnitude of pressure build up.

2.3.2.3 Jar Slake Test

The Jar slake test has been used to examine the slaking behaviour of chemically stabilised loess from Canterbury (Yetton, 1986; Glassey, 1986; Tehrani, 1988). The test involves determining the weight loss due to slaking of soil samples after they have been immersed in a container (jar) of water for a set time. Results are given as the percentage of the initial sample mass that remains coherent. Often the samples are subjected to a number of wetting and drying cycles (usually 5). After each cycle, the sample is weighed to determine the degree of slaking. The test was found to be an inexpensive and effective way of determining the durability of chemically stabilised loess. Howevr, unstabilised loess samples completely collapse in a matter of minutes when they are immersed in the container of water. Therefore this test would not be an effective way of comparing the slake resistance of different untreated loess samples.

2.4 Erosion Tests

2.4.1 Pinhole Test

The pinhole test has found particular application in testing to determine the stability of core material for earth dams. Results from the pinhole test have been quoted in many papers (e.g Cole et. al. 1977; Elges, 1985; Bell and Maud, 1994a; Coumoulos, 1977). It has been widely used on the loess deposits of Banks Peninsula (e.g Evans, 1977; Wilms, 1979; Schafer and Trangmar, 1981; Evans and Bell, 1981; Crampton, 1985; Glassey, 1986; Tehrani, 1988 and McDowell, 1986).

The most commonly used version of the pinhole test was developed by Sherard (1976a). In the test, water under head flows through a 1 mm pinhole in a soil sample. The test is run initially at a heads of 50 mm, 180 mm, 380 mm and 1020 mm. The eroding fluid is examined at the different heads and soils are classified as dispersive or non-dispersive according to the criteria shown in Table 2.2. According to Sherard et. al. (1976b) the extent of erosion in the pinhole test (as indicated by the colour of the water flow is indicative of dispersion. However, dispersion is only one of many factors which determines if a soil is erodible or not. In general, dispersive soils tend to be erodible. Not all erodible soils are dispersive however, therefore it is incorrect to make the statement that erosion equals dispersion.

Moore et. al. (1985) noted a discrepancy between standard dispersion tests and the pinhole test. The dispersion tests indicated that some soil samples were non dispersive, while the pinhole test indicated that they were dispersive. The author explains this discrepancy by saying that the soil was high in silt and prone to soil erosion rather than dispersion.

The above example illustrates the weakness of the pinhole test: it is not a reliable test of dispersion for soils in which factors other than dispersion play even a small role in determining the erodibility of a soil. When used as an erodibility test, it is useful in that it simulates practical erosion conditions in which the processes of slaking and clay mineral dispersion both influence the extent of erodibility.

Yetton (1986) proposed a modified pinhole test which measures erodibility rather than dispersivity. Soils are classified as erosive at a particular head if sustained erosion occurs for three or more minutes. For example, a soil which fails at a head of 50mm is give an erodibility class of E_{50}. Heads of 50, 180 , 380 and 1000 mm are used.

Schafer and Trangmar (1981) developed a quantitative pinhole erodibility test in which the "erosion index" of the soil was determined. The erosion index was arbitrarily defined as the increase in volume (ml) of the cavity which would be formed in a 50 mm long specimen by distilled water flowing at 3 ml/sec from a 1 mm diameter inlet, after 5 litres has flowed. The quantitative pinhole test was used extensively in this project.

2.4.2 Critical shear tests

Arulanandan et. al. (1975) developed a test in which the rate of surface erosion was measured. A cylinder of saturated soil was placed in a transparent cylinder filled with water. The transparent cylinder was rotated to speeds up to 1,500 rpm. The soil remains static while the rotation of the cylinder causes the water to move around the soil thus imparting shear stress on the soil sample. After a set testing time, the soil is weighed to determine the extent of erosion. A number of tests were carried out at different shear stresses and a linear relationship between shear stress and erosion rate was determined. From this relationship the critical shear stress (the shear stress required to initiated erosion) was calculated. The critical shear stress was taken as being representative of the erodibility of the soil.

Shaikh et. al. (1987 and 1988) carried out similar tests using a flume with compacted soil samples on the bottom. The flow rate was increased by tilting the flume. Using flow data from a venturi meter, the shear stress was calculated. The amount of erosion was defined as the difference between the dry weights of the samples before and after testing.

Arulanandan and Perry (1983) found critical shear stress to be an effective means of measuring soil erodibility:

"The mechanism of soil erosion is a complex phenomenon involving the structure of the soil and the nature of the soil and the nature of the interaction between the pore and eroding fluid at the surface. Because the critical shear stress is dependent on these factors it can be used as a fundamental parameter to classify erodibility characteristics."

Gray (1989) suggested that the flume and cylinder tests were surface erosion tests that were not particularly relevant to sub-surface erosion because eroded soil particles were essentially removed from the system whereas in sub-surface erosion, eroded particles remain in the seepage stream which is restricted by the hole that the water is moving through. According to Gray, high rates of particle erosion in narrow eroding streams can often result in hole plugging which will tend to suppress the rate at which the particles detach themselves into the eroding stream.

2.4.3 Water Jet Penetration test

Hill and Harrison (1980) developed a field test of loess erodibility known as the "Water-jet Penetration Test". The test involves spraying an in-situ loess deposit with a high pressure jet of water under standard conditions and measuring the penetration of the jet into the loess. At one site, a number of tests were carried out in order to determine the validity of the test. Using statistical methods it was shown that the differences in penetration corresponded well to visual changes in the soil profile. According to the authors the test has a number of advantages over conventional laboratory tests:

1. It only takes a few seconds to make a measurement.

Classification (Table 1) (1)	Head, in inches (2)	Test time for given head, in minutes (3)	Visual final flow through specimen, in milliliters per second (4)	Color of flow at end of test (cloudy or color) (5)	Hole size after test (needle diameter) (6)
D1	2	5	>1.5	Very distinct	2x
D2	2	10	>1.0	Distinct to slight	2x
ND4	2	10	<0.8	Slight but easily visible	1.5x
ND3	7-15	5	>2.5	Slight but easily visible	2x
ND2	40	5	>3.5	Clear or barely visible	2x
ND1	40	5	<5.0	Crystal clear	No erosion

Note: 1 in. = 25.4 mm.

Table 2.2: Criteria for evaluating pinhole dispersion (after Sherard, 1976a).

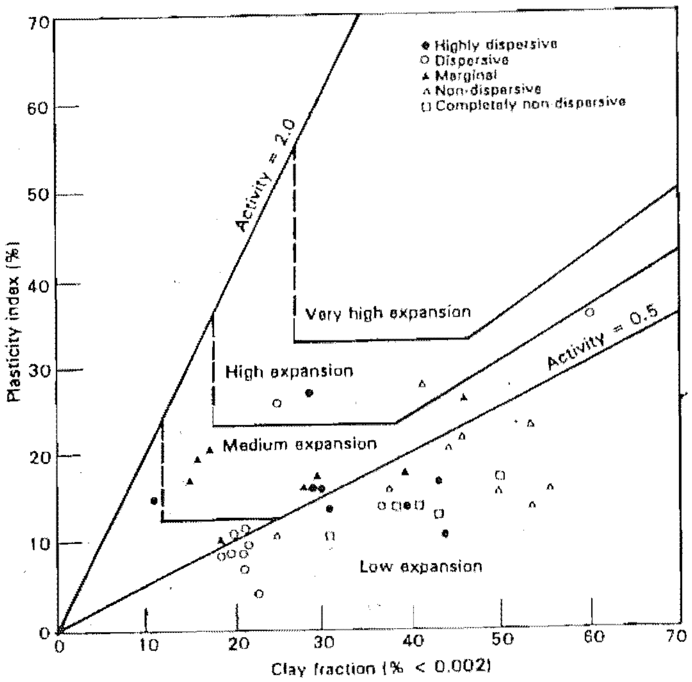


Figure 2.6: Activity chart showing the distribution of activities for soils with a range of dispersivities (after Bell and Maud, 1994).

2. Very little, if any laboratory work is required.
3. An in-situ assessment of loess characteristics is provided.
4. The method does not suffer from the limitations of low sample numbers.

The test seems to be an effective means of measuring loess erodibility. However, when considering the tunnel-gully erosion process, there are other factors affecting loess erodibility such as dispersion and slaking which the test does not measure.

2.4.4 Soil Index Tests

It is generally accepted that Atterberg limits provide little information on the erodibility of soils (Bell and Maud, 1994a; Arulanandan and Perry, 1983; Donaldson, (1975). However, Gerber and Harmse (1987) have found that soils with high plasticity indexes (over 35) tend to swell so much that potential flow paths get blocked off and erodibility is reduced. According to Paaswell (1970) the plasticity index (PI) gives a broad indication of erodibility; i.e soils with high PI are less prone to erosion than soils with low PI as a result of increased cohesion and particle bonding. Resendiz (1977) and Sherard (1972) both stated that soils of medium to low plasticity are most prone to erosion. Resendiz (1977) came to the conclusion that activity was a useful criterion for characterising erosive behaviour. However, a more recent study by Bell and Maud (1994a) indicates that the range of activities of erosive soils is so large that it is not possible to come to any conclusions (Fig. 2.6).

2.5 Rating Systems

Bell and Maud (1994a) suggested that a rating system using results from a number of different tests was the most practical way of identifying potentially erodible soils (Table 2.3). Yetton (1986) came to a similar conclusion and devised a scheme (Fig. 2.7) by which three characteristics were taken into account: dispersion (as determined by the crumb test), uniaxial expansion and erodibility (as measured by the pinhole test). Tests were carried out on soils exhibiting differing degrees of susceptibility to tunnel gully erosion, and it was found that the soils plotted in different regions of Figure 2.7. Based on the grouping of the different soils, three erosion risk classes: severe, high and low - moderate were proposed. Yetton made the statement that the classification scheme was

Crumb Test	Class Rating	Strong reaction 4	Moderate 2	Slight 1	No reaction 0
Dispersion Test	Class Rating	Highly dispersive 4	Moderately 2	Slightly 1	Non-dispersive 0
*ESP/CEC (meq/100 g clay)	Class Rating	Highly dispersive 5	Dispersive 3	Marginal 1	Non-dispersive 0
SAR	Class Rating	Over 10 3	2–10 1	Less than 2 0	
pH	Class Rating	Over 8 2	6–8 1		Less than 6 0

Highly dispersive = 18 and above; dispersive = 9–17; cautionary zone = 5–8; marginal = 1–4; non-dispersive = 0.
*Highly dispersive includes very highly dispersive. Non-dispersive includes completely non-dispersive of Gerber & Harmse (1987).

Table 2.3: Rating system for potentially dispersive soils (after Bell and Maud, 1994).

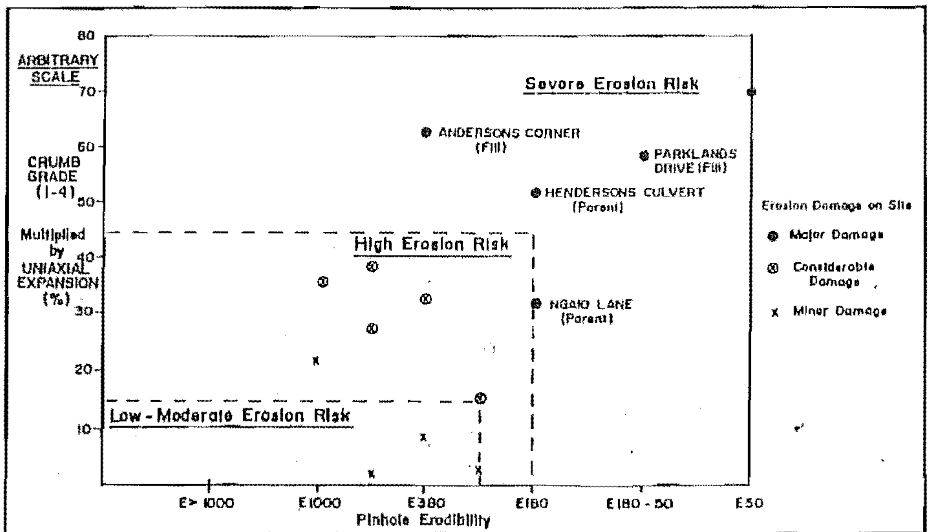


FIGURE 2.9 : A CLASSIFICATION OF EROSION POTENTIAL FOR BANKS PENINSULA LOESS BASED ON PINHOLE ERODIBILITY, UNIAXIAL EXPANSION, AND THE CRUMB TEST.

Figure 2.7: Classification of erosion potential for Banks Peninsula loess based on pinhole erodibility, uniaxial expansion and the crumb test (after Yetton, 1986).

based on arbitrary class limits and that more data was required before the system could be proposed with any confidence.

2.6 Synthesis

1. Slaking and clay mineral dispersion are the main processes which result in the sub-surface erodibility of the South Island loess deposits.

2. Clay mineral dispersion occurs when an electrical repulsive force is greater than an attractive Van der Waals force, so that in the presence of water, clay particles break away from the soil aggregates and go into suspension. The presence of sodium on the cation exchange complex of clay minerals is the main chemical factor contributing towards dispersive behaviour in soil.

3. Slaking is the disruption and collapse of the soil structure during saturation from water. Important factors affecting the degree of slaking as: rate of wetting, initial moisture content of soil, clay content, clay mineral dispersion, clay mineral expansion and the pore geometry of the soil voids.

4. The pinhole test is not a reliable test of dispersion for soils in which factors other than dispersion play even a small role in determining the erodibility of a soil. When used as an erodibility test, the pinhole test is useful in that it simulates practical erosion conditions in which the processes of slaking and clay mineral dispersion both influence the extent of erodibility.

5. Sub-surface erosion is a complex process involving many variables and consequently no one single test can be relied upon to predict field erodibility with absolute certainty. In light of this fact, it is desirable to design a testing programme in which all of the properties which are likely to have an affect on the extent of sub-surface erosion are investigated.

Chapter Three: Site Descriptions

3.1 Introduction

The locations of the six sites studied in this project are shown in Figure 1.1. When selecting site locations, two considerations were taken into account. The first was that the site be representative of the surrounding loess deposits, and the second was that it was possible to gain access (to depths of at least 2 m) to undisturbed soil which had not been dried by the sun. Sampling was generally restricted to the top 2 m because the main focus of this project, tunnel gully erosion is a near surface phenomenon. Four of the sites (Ahuriri, Gebbies Valley, Taiko and Wither Hills) were affected by tunnel gully erosion, whilst the other two sites (Barrys Bay and Timaru Downs) were free of tunnel gully erosion.

The six sites can be grouped into three geographic regions: the Timaru downs, Banks Peninsula and the Wither Hills. A description of the geology, Physiography, loess deposits and tunnel gully erosion of all three regions is given in this chapter. The sites in the three regions are then described in terms of erosion and soil profile characteristics.

3.2 Banks Peninsula Site Descriptions

3.2.1 Physiography and Geology

Banks Peninsula is dominated by the eroded calderas of the Lyttelton and Akaroa Volcanoes which were active during the mid to late Miocene (15-6 million years ago). The composite cones of the two major volcanoes consist of rubbly and massive aa-type basaltic and andesitic lava flows, ash beds, laharic deposits, cinder cones, trachyte dykes and domes. As volcanic activity decreased, the cones were dissected by radial drainage systems. Steep sided valleys were formed along drainage lines with ridges comprising of the more resistant lava flows. By the beginning of the Pleistocene, the present-day drainage patterns were well established (Weaver et. al., 1985).

At one time, Banks Peninsula was covered by podocarp forest. After European colonisation much of the forest was milled for timber or burnt off to clear land for pasture.

The replacement of native vegetation with pasture, and the resultant soil dessication, has been acknowledged as the principal "triggering factor" in the tunnel gully erosion on the Port Hills. Hughes (1970) scanned aerial photographs from the 1940's and 1960's and found little change in development in tunnel erosion since the 1940's. From this finding Hughes suggests that most of the tunnel gullies in Banks Peninsula are relict features corresponding to maximum vegetation removal prior to the 1940's.

The climate at low elevations around most of the Peninsula is subhumid (mean annual rainfall: 650-900 mm). At higher elevations, and at sea level in the eastern half of the Peninsula (i.e Akaroa harbour), the climate is humid with a mean annual rainfall in the range of 900-1400 mm (Griffiths, 1974). The north-eastern slopes which are in the rain-shadow of the south-easterly winds have an annual rainfall of about 600 mm (Molloy, 1988). In addition to the low rainfall, exposure to the hot afternoon sun and dry north-west winds make the north-eastern slopes of the Port Hills the driest in Banks Peninsula.

3.2.2 Loess Deposits

3.2.2.1 Origin

During the Pleistocene, the Waimakariri and Rakaia outwash fans infilled the area between the Southern Alps and Banks Peninsula. The sea level was at times more than 150 m lower than its present level (Raeside, 1964), and large areas of outwash fans were exposed to the east of Banks Peninsula. Glacial grinding produced considerable amounts of silt which was initially deposited on the outwash surfaces. The silt was then redeposited on the flanks of Banks Peninsula by the predominant Westerly winds. Griffiths (1974) suggests that much of the loess was redeposited down-slope by freeze and thaw processes during the Pleistocene. As a result loess deposits thin with altitude. The maximum loess thickness at a section near Birdlings flat, was found to be 16 m by Griffiths (1974). Several paleosols have been identified, although no satisfactory correlation with glacial episodes has yet been established (Goh et. al. 1977).

3.2.2.2 Distribution

Figure 3.1 shows the distribution of the two loess types described by Griffiths (1973) as occurring on Banks Peninsula. The principal features of both deposits are described below:

1) Birdlings Flat loess is found in the sub-humid zone (rainfall: 600-900 mm) usually below about 300 m. It has a maximum thickness of 16 m at the Birdlings Flat type section. There are two major soil layers, both of which contain prominent fragipans. The calcium carbonate present, may occur as either concretions or as filaments disseminated throughout the material. The soil which forms on Birdlings flat loess is known as the Takahe silt loam which is a sub-hydrous yellow grey earth.

2) Barrys Bay loess occurs in the humid climate zone (rainfall: 900-1400 mm) with a maximum thickness of 14 m at the type section in Barrys Bay. It is non calcareous and slightly finer than Birdlings Flat loess. According to Griffiths (1973), the finer texture of Barrys Bay loess is due to the fact that it is located further way from the major source area (the floodplain of the Waimakariri river). Three loess layers have been identified, and instead of fragipans a gammation zone occurs at the top of each layer. According to Griffiths (1973), the lack of a fragipan and the occurence of the gammation zone is due to increased weathering as compared to Birdlings Flat loess which occurs in a subhumid climate zone. The soil which forms on Barrys Bay loess is known as the Pawson silt loam, a hydrous to yellow-grey to yellow-brown earth.

Figure 3.2 shows the distribution of the major regolith types in relation to slope position on the Port Hills. In situ loess is primary airfall loess which has not been affected by slope movement processes, while loess colluvium has been affected by slope movement processes. During slope movement a component (up to 10%) of volcanic rock fragments are mixed in with the loess colluvium deposits which show distinct layering and are less compact than in-situ loess. Mixed colluvium consists of loess colluvium (10-90%) mixed with weathering products derived from volcanic rocks outcropping up-slope. Volcanic colluvium consists of weakly to moderately weathered volcanic rock fragments in a fine matrix which contains less than 10% loess colluvium (Bell and Trangmar, 1987).

3.2.3 Tunnel gully erosion

3.2.3.1 Distribution

Tunnel-gully erosion is a major problem associated with both rural and urban land use on Banks Peninsula. However, no quantitative estimate of the area which is affected by tunnel erosion has been made. Most of the tunnel gully erosion on Banks Peninsula

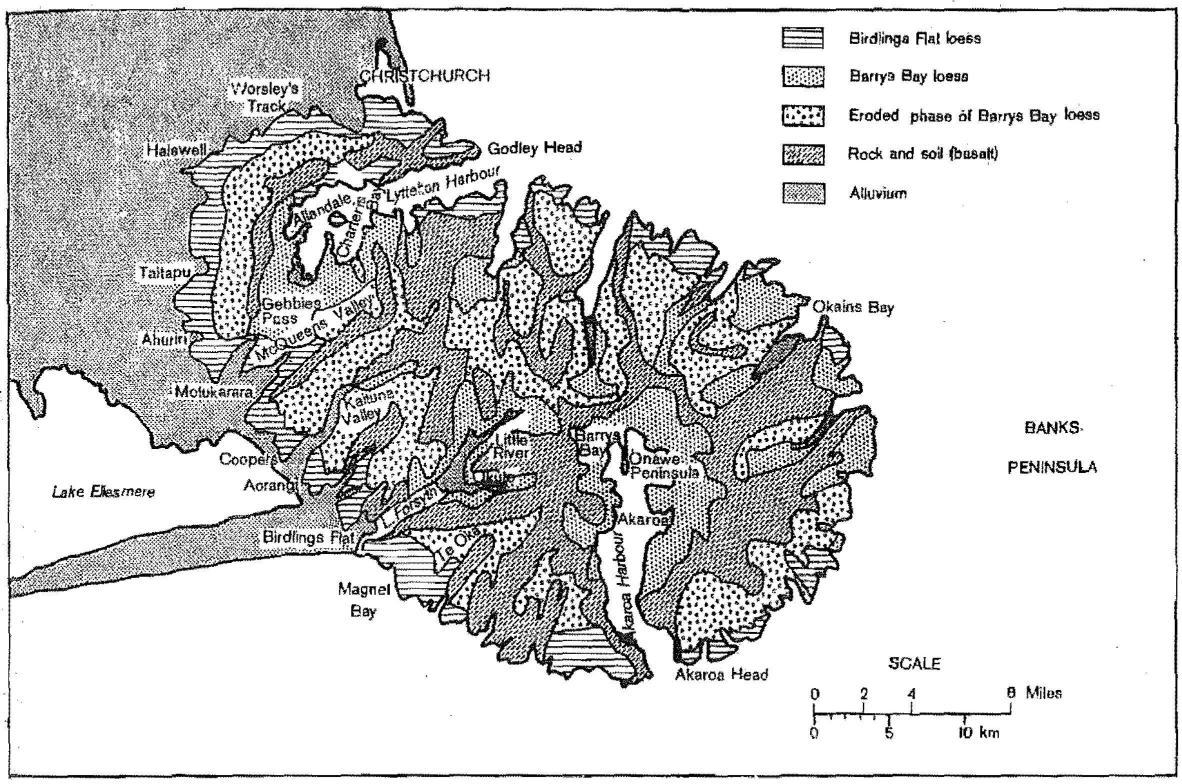


Figure 3.1: Distribution of loess on Banks Peninsula (after Griffiths, 1973).

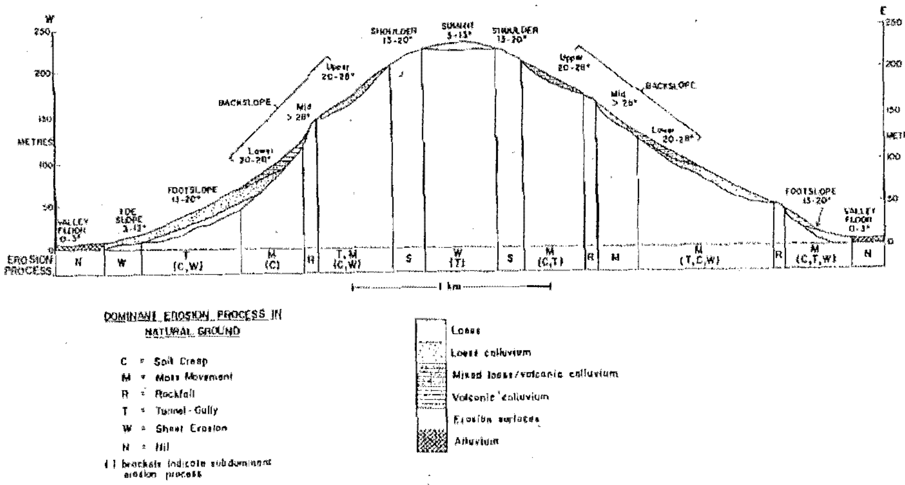


Figure 3.2: Generalised ridge cross-section showing relationships between landforms, slope, regolith and erosion on the Port Hills (after Bell and Trangmar, 1987).

occurs in Takahe fine sandy loam loam/Birdlings Flat loess. According to Griffiths (1974), the relatively dry climate in which Takahe soils form causes Takahe soils to be prone to tunnel gully erosion as a result of soil dessication cracks.

Pawson soils/Barrys Bay Loess deposits are found in the humid climate and are relatively free of tunnel gully erosion. This relationship suggests that climate has had an affect on the occurrence of tunnel gully erosion. It is not known whether geotechnical factors have also had an influence on the the lack of tunnel gully erosion. Hughes (1970) found that tunnel gully erosion is most common on slopes facing west to northwest below an altitude of 150 metres. According to Trangmar (1978) tunnel gully erosion is usually found either in the shoulder slope position in in-situ loess or in loess colluvium on the footslopes of the main ridges.

3.2.3.2 Previous work

The mechanisms of tunnel-gully erosion in Port hills loess and the soil properties affecting its occurrence have been well documented (Hoskings, 1962 and 1967; Hughes, 1970 and 1972; Miller 1971, Trangmar, 1976 and 1978; Evans, 1977; Wilms, 1979; Bates, 1979; Schafer and Trangmar, 1981; Lindley, 1985; Bell and Trangmar, 1987). Bell and Trangmar (1987) provide models for the formation of shallow and deep tunnel systems in Takahe soil profiles (Fig. 1.3). It is is generally accepted that Birdlings Flat loess, (which covers the Port Hills) is dispersive and erosive, and that tunnel gully erosion was initiated by the destruction of native vegetation followed by over grazing after the arrival of European settlers. To date, there has been no studies carried out on the Geotechnical properties of Barrys Bay loess.

The fragipan (C_x horizon) is generally regarded as being more resistant to erosion than the other horizons as a result of its lower porosity and higher density (Evans, 1977; Schafer and Trangmar, 1981; Yetton, 1986). Using a quantitative pinhole test method on undisturbed material, Schafer and Trangmar (1981) determined that C_x horizon soil was 5 to 10 times less erodible than soil from the C horizon. When the same test was carried out on recompacted material they found that: a) the erosion resistance of both soils was dramatically reduced and b) the C_x soil was now only 2.5 times more resistive to erosion that the C soil. The fact that the C_x soil was still more resistive to erosion in the recompacted state (when densities were the same) suggests that other properties apart from just density makes the C_x horizon more resistive to erosion. Quantitative pinhole testing shows that the A and B horizons are non erodible (Schafer and Trangmar, 1987; Trangmar, in prep.). This finding is interesting given the fact that much of the tunnel erosion on the Port Hills is initiated in the B horizon, and it seems to indicate a weakness in the ability of the pinhole test to predict tunnel gully erosion.

Trangmar (in prep.), Miller (1971) and Yetton (1986) found that in general, clay mineral dispersion increases with soil profile depth. The increase in dispersion tendency with depth has been attributed to an increase of exchangeable sodium and a decrease of organic carbon with depth. Miller (1971) found that the exchangeable sodium percentage (ESP) increased from 0.9 in the A horizon to 41 in the C horizon.

The A horizon is non dispersive (Trangmar in prep.; Miller, 1971; Yetton, 1986). The B horizon has variously been described as non dispersive and dispersive: contrasting SCS dispersion test results have been determined by Miller (1971) (20%) and Trangmar (in prep.) (83%). Also, a large crumb class variation (2-4) has been observed (Yetton, 1986).

Using the SCS dispersion test, both Miller (1971) and Trangmar (in prep.) found the C horizon to be highly dispersive (100% dispersion). Like the B horizon, a large variation in crumb class (2-4) has been observed (Yetton, 1986). The Cx horizon is usually found to be slightly less dispersive than the C horizon: dispersion test results range from 41-64% (Miller, 1971; Trangmar, in prep.); crumb test results range from 2-3. The lower dispersivity of Cx horizon material may explain why compacted Cx horizon material was found by Schafer and Trangmar (1981) to be less erosive than C horizon material. According to Trangmar (in prep.), the fragipan has a considerably higher clay content than the underlying parent material. The higher clay content may also cause the fragipan material to to be more resistive to physical erosion by flowing water. Miller (1971) found that slaking was a significant factor in the tunnel gully erosion process. Miller also came to the conclusion that seasonal shrinkage of the soil mass was of prime importance in allowing access of water through soil cracks, followed by dispersion and slaking leading to the formation of tunnels.

The above results were determined with samples from a wide variety of locations on the Port Hills. The large result variability suggests that Port Hills loess is quite variable in its properties from site to site. To date no systematic survey has been carried to determine the spatial variability of the erosive/dispersive properties of Port Hills loess.

3.2.4 Ahuriri Site Description

The Ahuriri site is located on the South Western flanks of the Port Hills which comprise the northwestern part of Banks Peninsula (Fig. 3.3). Figure 3.4 shows the slope from where the auger samples were taken. Like most of the surrounding hillsides, the slope has been severely affected by tunnel-gully erosion. The average slope gradient is about 20° and the slope faces towards the west. The gully walls on the slope have an average depth of about 2 m, and a maximum depth of about 5m. The open gullying stops about two thirds of the way up the slope. Above this, shallow, partially collapsed tunnels with an approximate depth of about 0.5 m continue to near the top of the slope. At the slope shoulder the soil thins considerably and the underlying basalt is occasionally revealed.

Ten 2 m deep auger holes were sunk in to a hill slope to obtain disturbed material for laboratory testing and to provide soil profile information. The 2 m deep auger holes were deep enough to provide access to the C horizon. In order to obtain soil samples that were representative of the slope as a whole, the auger holes were taken at regular intervals from the toe to the shoulder of the slope. All tube and bulk samples were taken from recently excavated faces of the Ahuriri quarry (which was located on the opposite side of the valley). Eroded tunnel gully faces were used to describe soil profile characteristics. The most obvious feature of the soil profile was the fragipan which protruded from the gully walls (Fig. 3.5). The soil profile described in Figure 3.6, was a typical Takahe Silt loam profile formed on Birdlings Flat loess.

The Ahuriri loess quarry (Fig. 3.7) which has been cut to a depth of about 16 m, provided an opotunity to investigate the properties of loess at depths greater than 2 m. Selected geotechnical properties of Ahuriri quarry loess are given in Chapter 5. A brief description of Ahuriri quarry loess is given below.

Calcite, usually in the form of filaments in ancient root holes/soil fractures, was found in most areas of the quarry. However, no evidence of calcite precipitation was found in the top 1.5 m. A number of calcite concretions up to 7 cm long and 3 cm thick were found in different parts of the quarry. Calcite concentration was quite variable and it

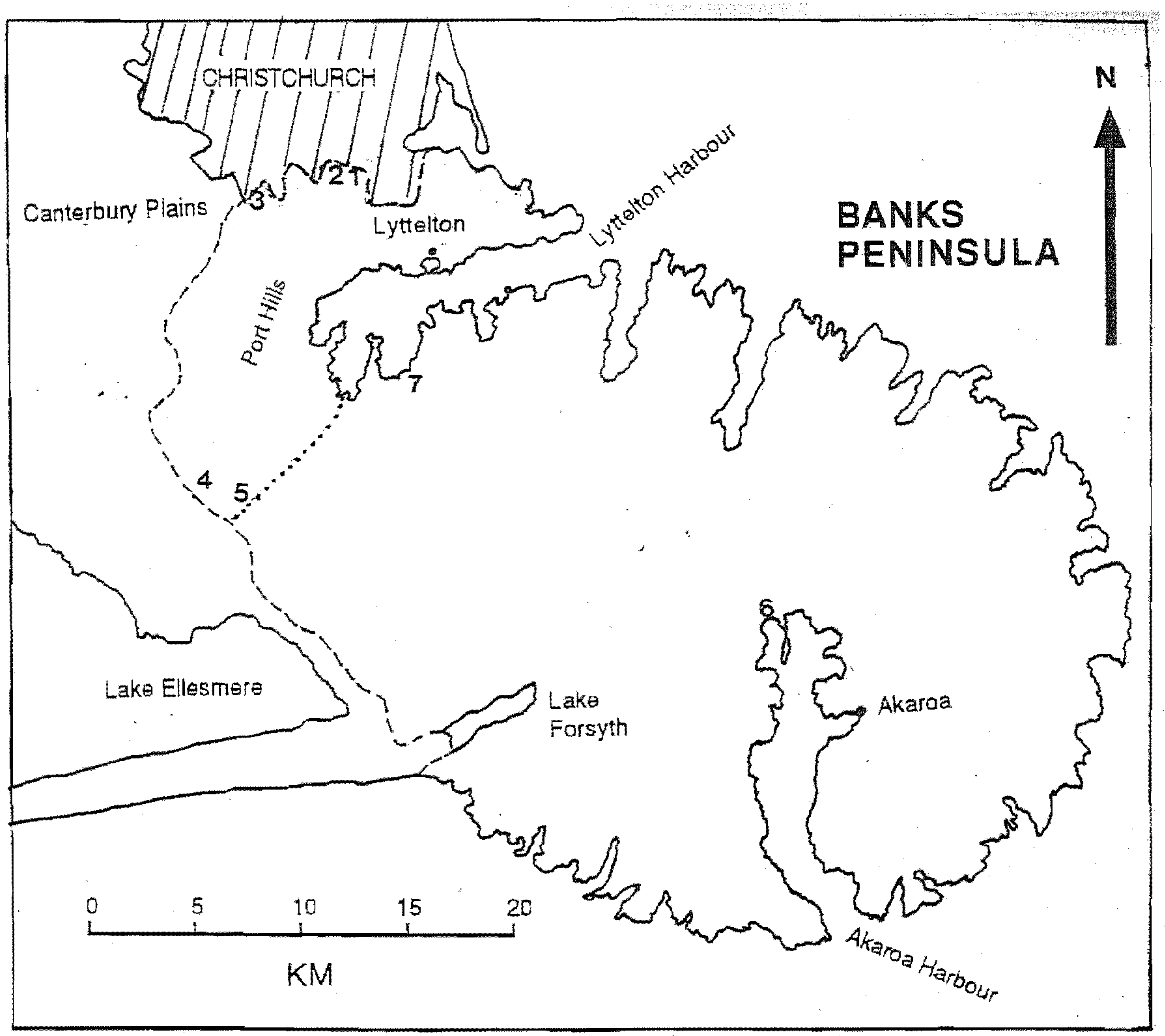


Figure 3.3: Banks Peninsula site location map. 1 = Glenelg spur, 2 = Whaka terrace, 3 = Westmoreland, 4 = Ahuriri sampling site, 5 = Gebbies Valley sampling site, 6 = Barrys Bay sampling site, 7 = Charteris Bay.

Figure 3.4: Tunnel gully affected slope at the Ahuriri site

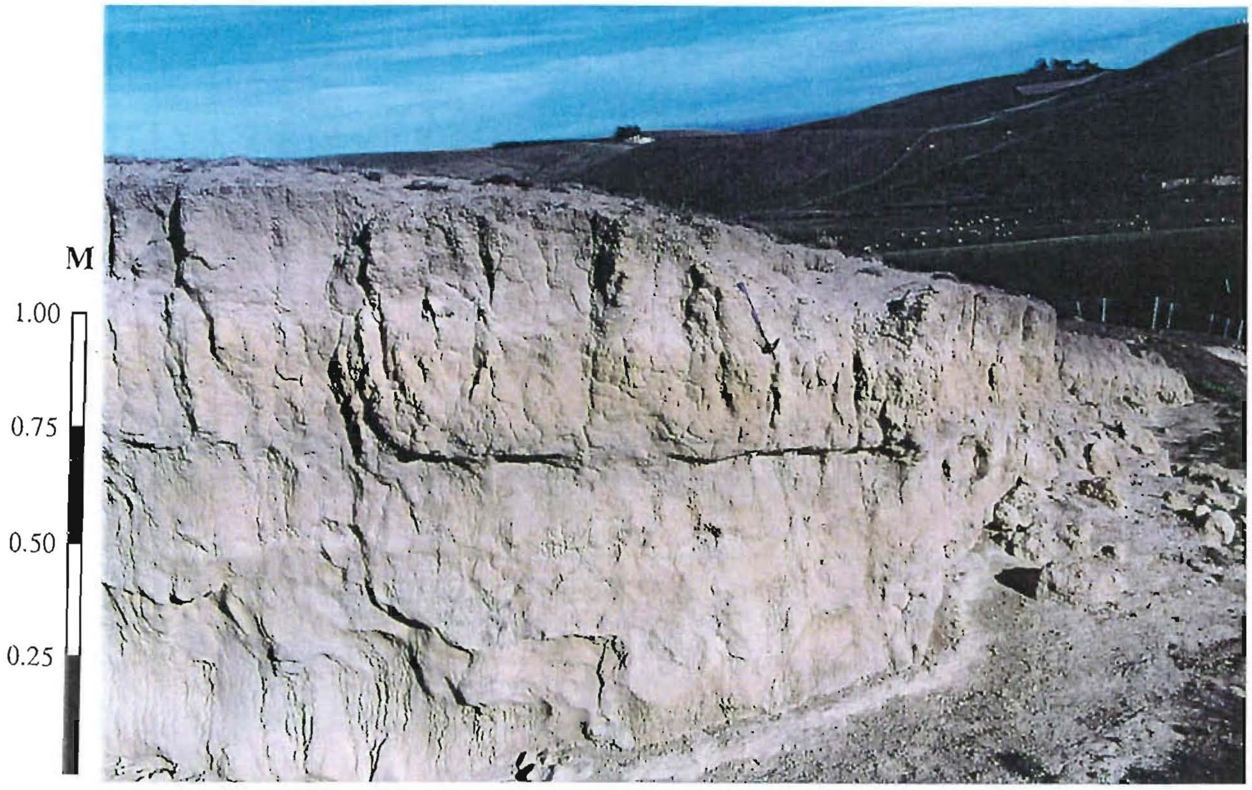
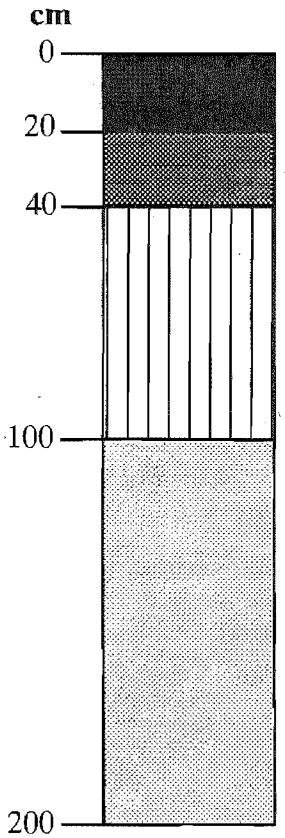


Figure 3.5: Soil profile at the Ahuriri site showing the fragipan which is typical of Takahe silt loam soils.



Horizon	Soil Material	Structure and Weathering
A	Moist, soft, dark greyish brown clayey silt with some fine sand. Top soil with many roots (OL).	Weakly developed medium crumb.
B	Moist, soft, yellowish grey, clayey silt with some fine sand, with about 50% organics. (OL).	Moderately developed coarse subangular blocky.
C_x	Slightly/moderately weathered, dry, very compact, yellowish brown silt with some clay and fine sand with about 20% organics. fragipan (ML).	Weakly developed very coarse prismatic. Reddish brown gley mottling affects about 40% of the soil.
C	Slightly weathered, dry, compact, greyish brown, silt with some clay and sand. loess parent material (ML).	Massive. Gley mottling affects about 10% of the material.

Figure 3.6: Representative soil profile of the top 2 metres of Ahuriri loess. See Appendix B for an explanation of soil terminology.

Figure 3.7: The Ahuriri loess quarry.

did not seem to occur in distinct layers.

Auger holes were drilled on each of the three quarry platforms. In this way it was possible to construct a 17 m deep soil profile (Fig. 3.8). Bedrock was not encountered, and as a result 17 m is the minimum thickness of loess. A loess depth of at least 17 m is significant in that it is deeper than the 16 m maximum loess depth observed by Griffiths (1973). Field inspection showed that the C horizon of the modern soil profile had a significantly higher clay content than the loess at depths greater than 2 m. Another layer of loess with a texture similar to the modern C horizon was identified between the depths of 11.8 to 13.8 m. Five distinct silt rich/clay poor layers were identified as being slightly coarser than the bulk of the loess. Figure 3.9 shows the upper three silt rich/clay poor layers exposed in the face of the quarry. Except for the top 1.5 m, calcite filaments were found at all depths in the profile. Two main areas of calcite concentration were found between: 1.7 - 2.3 m and 7.6 - 10.1 m.

3.2.6 Gebbies Valley Site Description

The Gebbies Valley site is located on the Eastern fringe of the Port Hills (Fig. 3.3). Figure 3.10 is an aerial photograph, showing the distributiion of tunnel gully erosion on the site. Basalt outcrops are situated at the head of the slope. Below these outcrops is a deposit of basalt colluvium which grades downslope into loess colluvium. The hill-slope has an average gradient of about 22° and a SE facing orientation. Like the Ahuriri site, open gullying was the most common form of erosion. The average open gully was about 1.5 m deep and two to three metres wide and the deepest gully was about 6 m deep.

Nine auger holes were used to determine soil profile characteristics and collect material for laboratory testing. Eight holes were drilled to a depth of about 2 m. To ensure representative sampling, the holes were distributed over the whole site area. No bedrock was encountered in any of the holes. However, occasional gravel sized basalt clasts were encountered in most of the holes and as a result the soil was classified as loess colluvium. Except for an increase in the volcanic clast content towards the head of the slope, the soil profile was reasonably constant from place to place. The soil profile which is described in Figure 3.11, was very similar to the Ahuriri soil profile, and is typical of a Takahe silt loam formed on Birdlings Flat loess.

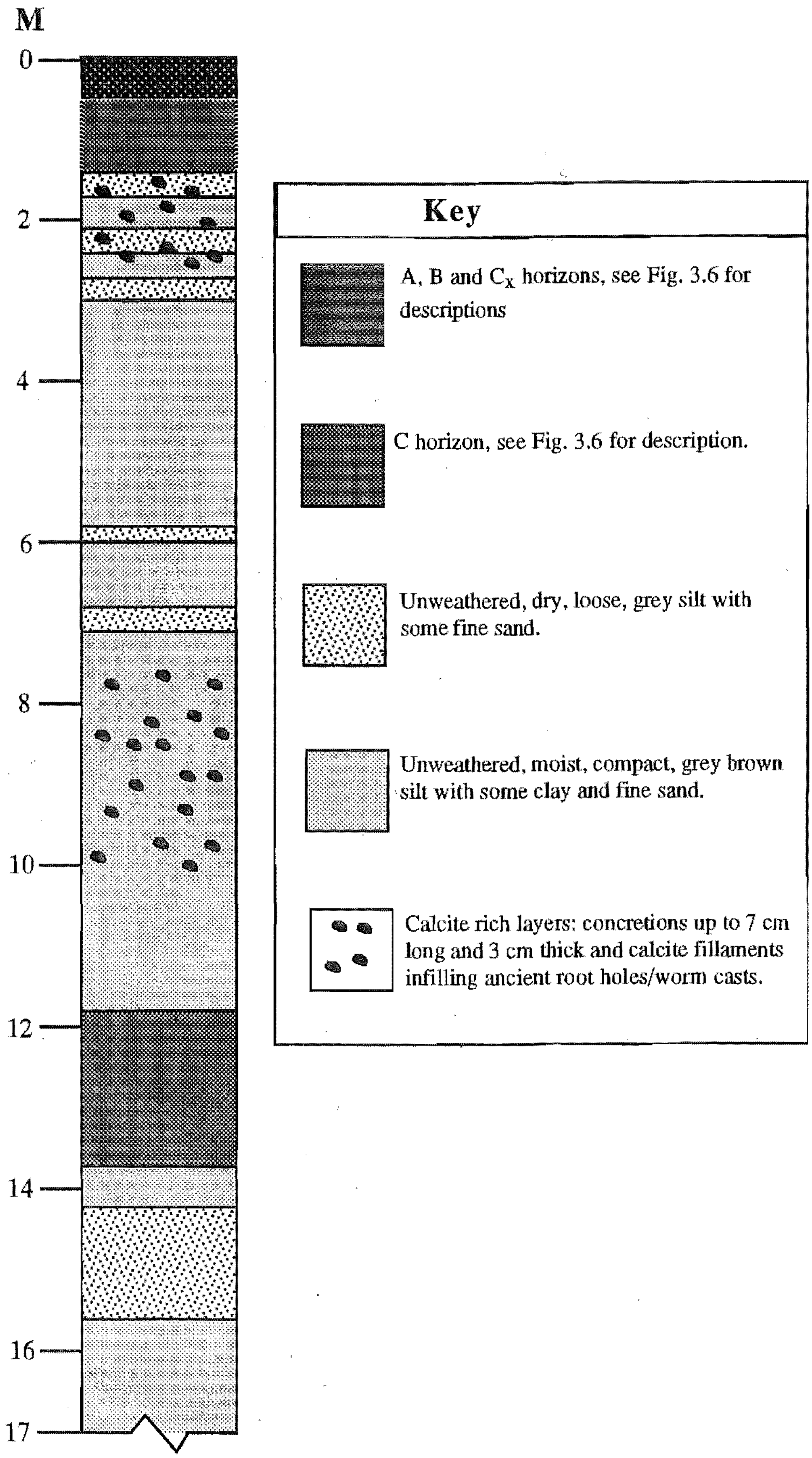


Figure 3.8 Auger hole log for Ahuriri quarry loess.

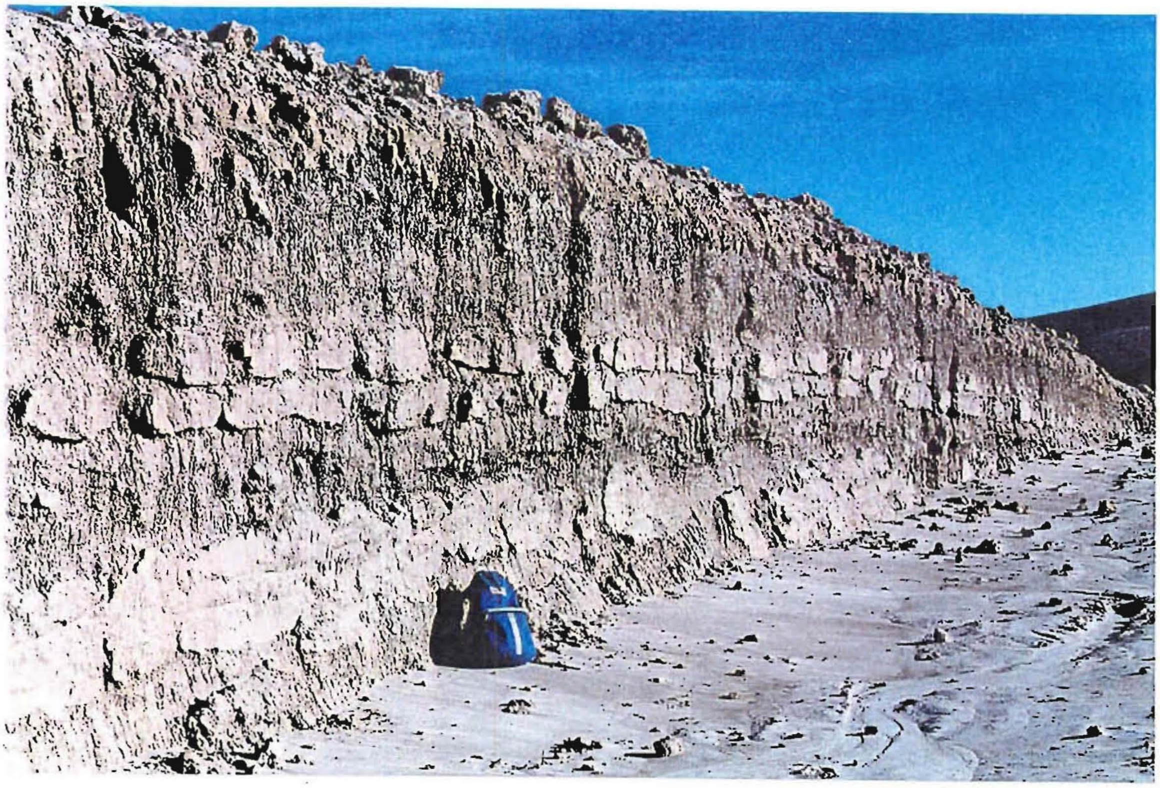
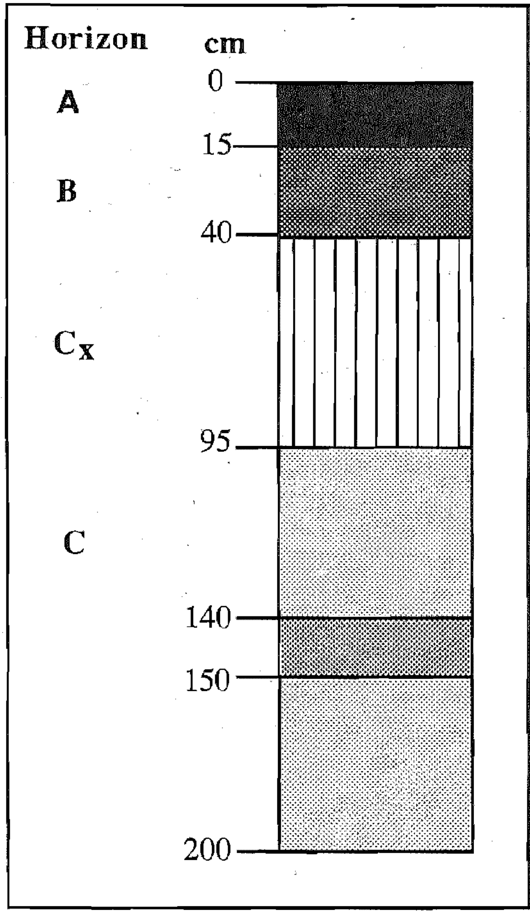


Figure 3.9: The upper three clay poor/silt rich layers as they are exposed in the Ahuriri loess quarry (Back pack for scale = 50 cm).

Figure 3.10: Aerial photograph of the Gebbies Valley site. Scale: 1 : 5280.



Soil Material	Structure and Weathering
Moist, soft, dark greyish brown clayey silt with some fine sand. Top soil (OL).	Weakly developed medium crumb.
Moist, soft, greyush brown clayey silt with some fine sand and 60% organics (OL).	Moderately developed coarse subangular blocky
Moderately weathered, moist, compact, yellowish brown clayey silt with some clay and fine sand. Fragipan (ML).	Weakly developed very coarse prismatic. Reddish brown gley mottling affects about 50% of the soil.
Slightly weathered, moist/dry, compact, greyish brown silt with some clay and fine sand. Loess colluvium (ML).	Massive. Gley mottling affects about 10% of the soil.
Dry, loose, brownish grey silt with some fine sand.(ML)	Massive.
Slightly weathered, moist/dry, compact, greyish brown silt with some clay and fine sand. Loess colluvium (ML).	Massive.

Figure 3.11: Representative soil profile of the top 2 metres of Gebbies loess-colluvium. See Appendix B for an explanation of soil terminology.

All tube and bulk samples were taken from a gully wall. The wall faced south and had not been significantly dried by the sun. Gully walls were also used to determine soil profile characteristics. Soil structure was most easily identified on the dry, North facing walls.

3.2.7 Barrys Bay Site Description

The site is located at the base of a slope covered by Barrys Bay loess which is not affected by tunnel gully erosion. An actively eroding headscarp of a small landslide provided access to soil to a depth of about 3 m. The headscarp has a SE orientation and the exposed soil had been subject to only minimal drying by the sun. The soil face was used to provide soil profile information and to collect tube samples for laboratory testing.

Two auger holes were drilled just above the face to obtain fresh material for laboratory testing and also to compliment the soil profile information obtained from the soil face. Figure 3.13 shows the soil profile profile log from the Barrys Bay site. The most obvious feature in the soil profile is the gammation zone between depths of 0.3-0.65 m which is a typical characteristic of soils formed on Barrys Bay loess. Figure 3.12 shows a soil profile revealed in a road cutting showing the gammation zone which penetrates both horizontally and vertically into soil defects.

Figure 3.12: The Barrys Bay loess gammation zone.

Horizon	cm	Soil Material	Structure and Weathering
A	0–30	Moist, dark greyish brown, clayey silt with some fine sand. Top soil (OL).	Weakly developed medium crumb.
B1	30–50	Moderately weathered, moist, soft, greyish brown silt with some clay and fine sand with about 30% organics (ML/OL).	Weakly developed fine subangular blocky.
B2	50–100	Moderately/highly weathered, moist, soft, greyish brown silt with some clay and fine sand with about 10% organics (ML).	Weakly developed medium blocky with a nett gammate structure. Gley mottling affects about 70% of soil. Gammation veins penetrate into C horizon.
C	100–200	Slightly weathered, moist, compact, greyish brown silt with some clay and fine sand (ML).	Moderately developed very coarse prismatic with gammation veins in upper 1 m. Gley mottling affects about 50% of the soil.

Figure 3.13: Representative soil profile of the top 2 metres of Barrys Bay loess. See Appendix B for an explanation of soil terminology.

3.3 Timaru Downs

3.3.1 Geology and Physiography

The basement rock is weakly schistose greywacke which is part of the Triassic to Permian Haast Schist Group which was peneplained in the late Mesozoic. Upper Cretaceous and lower Tertiary sediments were deposited over the basement rock until the Oligocene when regression of the sea took place. The upper Tertiary non-marine cannington gravel was then deposited on a slight angular unconformity. The Tertiary deposits are overlain by the 2.5 Ma Timaru Basalt lava flow which outcrops over an area of about 130 km^2 immediately to the west of Timaru. At the coast near Timaru, the basalt is 2 - 7 m thick. The basalt rises gently to the west so that at Mt Horrible, it's westernmost outcrop some 16 km west of Timaru, it reaches an altitude of about 350 metres and a thickness of about 25 m. The basalt is very strong and it has been used as a building stone in the South Canterbury area for more than 100 years.

The Basalt has protected the underlying units from significant erosion, with the result that the area covered by the lava flow is raised above the surrounding downlands. This raised area is known as the Timaru downs, which form a part of the South Canterbury Downlands and cover an area of approximately 145 km^2. Over most of this area, the Timaru basalt is covered by a blanket of loess up to 19 metres thick (Tonkin et. al. 1974). Most of the South Canterbury downs area is covered by at least 1 m of loess or loess-derived soil such asloess colluvium (Bruce et. al. 1973).

The climate of the South Canterbury downlands is subhumid, with an annual rainfall of about 600-800 mm. Summer droughts are very common (Molloy, 1988). The original native forests were cleared by European settlers and the land is now mainly used for intensive livestock farming.

3.3.2 Loess deposits

The major source of the loess deposits of South Canterbury were the large coalescing alluvial fans of glacial origin forming the Canterbury plains and their seaward extension. Early workers believed that the Timaru (and Banks Peninsula) loess deposits were of marine (Hutton, 1882 and 1905; Wild 1919), or volcanic (Goodall, 1886) origin. Hardcastle (1889 and 1908) and Von Haast (1865) advocated an aeolian origin. Raeside

(1964) provided extensive evidence for an aeolian origin and identified six distinct loess layers which were tentatively correlated with glacial events. The recognition of paleosols with comparable morphology to surface soils allowed Tonkin et. al. (1974) to identify six loess members. In each of the six loess members, fragipan layers with well defined vertical joints filled with grey gammate veins were identified. Using C^{14} dates from peat samples lieing above and below the upper loess layer, Goh et. al. (1978) found that the modern soil was developed from the present day to 10,000 years B.P and that the second layer was deposited before 49,700 years B.P. Due to limited C^{14} dating data, no satisfactory correlation with glacial events has yet been made.

According to Kear et. al. (1967) two soil profiles have developed on the loess blanketing the Timaru Downs: the subhydrous/sub-humid Timaru silt loam and the dry hydrous/sub-humid to humid Claremont silt loam.

3.3.3 Tunnel gully Erosion

According to Laffan and Cutler (1977b) and Tonkin (pers. com.), the loess that blankets the Timaru downs unaffected by tunnel gully erosion. An inspection of aerial photographs of the Timaru downs showed that these statements are generally correct, and that the rest of the South Canterbury downlands are also largely free of tunnel gully erosion. However, reconnaissance surveys of the downlands using aerial photographs identified two areas of tunnel gully erosion. The first is located in the upper Pareora river region (30 km inland from Timaru, grid reference: J38 400/520), and the second is located on the slopes on the SW side of the Timaru Downs (Fig. 3.14). Due to time constraints, the Pareora site was not investigated. A literature search revealed that no work has been carried out on tunnel gully erosion in the South Canterbury area.

Although tunnel gully erosion does not affect Timaru loess in its undisturbed state, field observations showed that recompacted Timaru loess is prone to subsurface erosion. Extreme subsurface erosion resulting in roof collapse was observed in recompacted loess at the Timaru Harbour Board basalt quarry (location: Fig 3.14). Figure 3.15 shows one of the largest collapse holes which was 1.4 m wide and 2.2 m deep. Figure 3.16 shows a series of collapse holes resulting from a single tunnel. As Figures 3.15 and 3.16 show, the fill material was devoid of any significant grass or topsoil. Given the mechanism of sub-

Figure 3.14: Showing: A) The location of the Timaru Downs sampling sites: 1 = Taiko sampling site, 2 = Road cutting, 3 = Timaru harbour board quarry, and B) The area affected by tunnel gully erosion (which is enclosed by black lines).Scale: 1.5 cm = 1 km. Source: NZMS 260, sheet P28.

Figure 3.15: Collapse hole resulting from sub-surface erosion in filled loess at the Timaru harbour board quarry.

Figure 3.16: Three roof collapse holes resulting from a single tunnel.

surface erosion (section 1.4.2) it is likely that the lack of top soil and grass encourages the development of sub-surface erosion as a result of increased dessication cracking of the soil.

3.3.4 Site Descriptions

3.3.4.1 Timaru Downs

The locations of the two Timaru Downs sites are shown in Figure 3.14. Site 1 was located at a road cutting where a recent slip had revealed a soil profile which had not been significantly dried by the sun. Two auger holes were drilled just above the slip and tube samples were taken from the face of the slip. The second site was at the Timaru Harbour Board Quarry. At this site two auger holes were sunk in the undisturbed loess above the main quarry face and the exposed loess profiles at the quarry provided soil profile information.

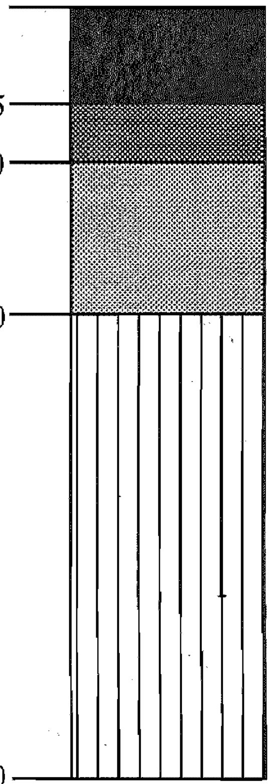
The soil profiles at both sites were found to be approximately the same (Fig. 3.17). The most obvious soil profile feature are the well defined vertical joints of the fragipan (Fig. 3.18) which are filled with grey clayey silt gammate material. At the Timaru quarry, the fragipans of the top three loess layers were identified (Fig. 3.19). The upper fragipan layer was found to be about about 2 m thick. Tonkin et. al. (1974) also observed that the upper fragipan was about 2 m thick.

3.3.4.2 Taiko

The Taiko site is located in the tunnel gully affected area on the western fringe of the Timaru Downs (Fig. 3.14). Most of the tunnel gully erosion in the area is less than 1 m deep (Fig. 3.20) Figure 3.21 shows a typical example of one of the shallow, partially collapsed tunnels. The top of the tunnel is 0.3 m deep, the base is 1 m deep and it is approximately 0.6 m wide. No evidence of deeper tunnelling was found.

Figure 3.22 shows the slope from which the soil samples were taken. The average slope gradient is about 21° The head of the slope is composed of Timaru basalt colluvium. The underlying Tertiary sandstone was identified in the road cuttings and at the bottom of some of the larger gullies at a depth of about 5 m.

The tunnel gully erosion, in the open gully form, occured from the shoulder to the foot of the slope. The average gully was found to be about 2.5 m deep and 4 m wide. The



Horizon	cm	Soil Material	Structure and Weathering
A	0–25	Moist, soft, dark greyish brown clayey silt. Top soil with many roots (OL).	Moderately developed fine granular.
B_1	25–40	As above but with about 30% loess material (OL).	Weakly developed medium blocky.
B_2	40–80	Highly weathered, moist, soft, yellowish brown clayey silt with about 30% organics (ML/OL).	Weakly developed coarse blocky. Reddish brown gley mottling affects about 80% of the soil.
C_x	80–200	Slightly weathered, moist/dry, compact, yellowish brown clayey silt. Fragipan (ML).	Strongly developed very coarse prismatic with a gammate structure. Gammation veins with widths of about 5 cm occur between the soil columns. Reddish brown gley mottling affects about 50% of the soil.

Figure 3.17: Representative soil profile of the top 2 metres of Timaru loess. See Appendix B for an explanation of soil terminology.

Figure 3.18: Vertical joints in the Timaru loess fragipan.

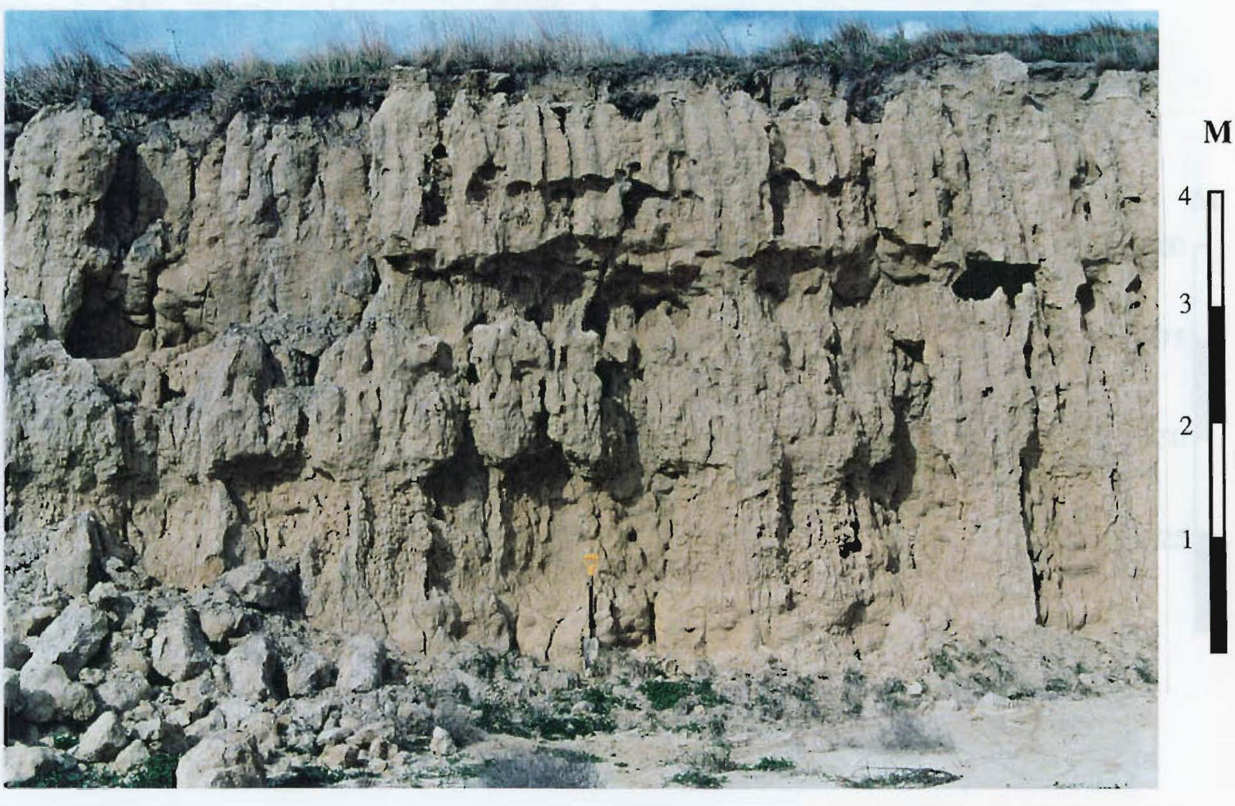


Figure 3.19: Soil profile showing the fragipans of the upper three Timaru loess layers which protrude from the face. The top of the third fragipan can be seen just below the spade handle.

Figure 3.20: Typical example of shallow tunnel gully erosion in the Taiko valley

Figure 3.21: Section of a typical shallow tunnel formed in the Taiko valley.

Figure 3.22: The Taiko sampling site.

Figure 3.23: The wall of the deepest tunnel-gully on the Taiko site.

Horizon	cm	Soil Material	Structure and Weathering
A	0–30	Wet, Soft, dark greyish brown clayey silt with some sand. Top soil with many roots (OL).	Moderately developed medium granular.
B_1	30–50	Intermediate between A and B_2.	Moderately developed coarse blocky. Reddish brown gley mottling affects about 10% of the soil at the top and 60% at the base.
B_2	50–105	Moderately weathered, moist, soft, yellowish brown clayey and fine sandy silt with occasional fine gravel. About 50% organics at top, 10% at bottom. Weathered Loess-colluvium (ML).	
C	105–200	Non weathered, dry, compact, yellowish brown clayey and fine sandy silt with occasional fine gravel with about 10% organics. Gravel content increases downwards. Loess Colluvium (ML).	Massive, reddish brown gley mottling affects about 10% of the soil.

Figure 3.24: Representative soil profile of the top 2 metres of Taiko loess-colluvium. See Appendix B for an explanation of soil terminology.

largest gully was 5 m deep and 10 m wide (Fig 3.23).

As indicated by the forestry tracks and the many pinus radiata stumps, the site had recently been used for forestry, probably indicating that the land owner who planted the trees considered that the tunnel gully erosion had rendered the slope unsuitable for grazing. The two other ex-forestry areas found nearby are also on tunnel gully effected areas.

To obtain samples that were representative of the whole slope, eight auger holes were drilled from the toe to the shoulder of the slope. Tube samples were obtained from the forestry road cuttings, the larger of which gave access to soil at a depth of 2 metres. Recent soil debris covering the cuttings ensured that the soil had not been dried by the sun.

Figure 3.24 shows the Taiko soil profile. In contrast to the Timaru profile, the Taiko profile shows no evidence of a fragipan. The soil was classified as loess colluvium (as defined by Bell and Trangmar, 1987) because fragments of the underlying Tertiary sandstone were often encountered during augering.

3.4 Wither Hills

3.4.1 Physiography

The Wairau Conglomerate, a weakly cemented, poorly sorted greywacke conglomerate with sandstone and mudstone beds forms the core of the Wither Hills (Rae and Tozer, 1990). Little work has been done on the Wairau Conglomerate. However, it is known that it is Pliocene in age. The conglomerates rest unconformably on Torlesse greywacke. During the Kaikoura orogeny, the Torlesse basement rocks were divided into a number of major crustal blocks. The uplift and rotation of these blocks resulted in tilting (up to 20°) and as a result, the overlying Pliocene conglomerates were eroded so that they are now only preserved in fault depressions (Rae and Tozer, 1990). The remaining conglomerates were eroded during the late Pleistocene to form the present landscape of narrow valley bottoms, moderately steep hillsides (21-30°) and narrow ridges rising to a maximum altitude of 422 m.

The climate is subhumid with an evenly distributed average rainfall of 650 mm. Summer droughts are common. Mean February temperature is 18 °C and mean July temperature is 7.2 °C (Laffan and Cutler, 1977a). Pre-European vegetation consisted of a dense cover of silver tussock. After European settlement, burning caused a considerable depletion in the native vegetation which was replaced with introduced pasture. Overgrazing by stock and rabbits and frequent droughts resulted in considerable pasture depletion.

3.4.2 Loess Deposits

During the Pleistocene, glaciers extended down the upper Wairau valley. The outwash fans of these glaciers (the Wairau Plains) were the source of the Wither Hills loess deposits. Chlorite III schists (on the north side of the valley) and Torlesse greywacke (on the South side of the valley) comprise the basement rocks which provided most of the material to the Wairau plains. The lower slopes of the Wither Hills are covered with non calcareous, quartzo-feldspathic loess up to a maximum thickness of 7 m (Laffan and Sutherland, 1988). Most of the loess was reworked to form a variable cover of loess colluvium containing some of the underlying gravels. On headslopes and at altitudes above 200 m, the loess is very thin or absent. The soil which has formed on the loess and loess colluvium is known as the Wither silt loam which is classified as a sub-hydrous yellow-grey earth (Laffan and Cutler 1977a).

3.4.3 Tunnel Gully Erosion

The most severe tunnel gully erosion in New Zealand occurs on the Wither Hills (Lynn and Eyles, 1984; Gibbs, 1945). The formation of tunnel gully erosion was dramatically accelerated by the onset of pastural farming about the middle of last century with burning and over-grazing of the native grassland. It is thought that the formation of cracks and cavities in the soil would have been greatly facilitated by rabbit burrowing, particularly during the period of heaviest infestation prior to 1900 (Laffan and Sutherland, 1988).

Taylor (1938) was the first to describe the occurrence of tunnel gully erosion on the Wither Hills. Calling it 'tunnel' erosion he described it as occurring on the hills bordering the Wairau Plains. Gibbs (1945) wrote a paper on the tunnel-gully erosion on the Wither Hills and he described it as the most extensive example of tunnel-gully erosion in New Zealand. According to the soil survey carried out, there were 36 ha of Wither silt loam, and not one unit area of 0.2 ha was uneroded.

Laffan and Cutler (1977b) made field observations and suggested a sequence for the formation of tunnel gully erosion in Wither Hills loess. Many large cracks up to 3 mm wide extending down into the clay rich B2 horizon were observed, and profile sections showed that most tunnels formed in the B2 horizon. The widest uncollapsed tunnels (up to 71 cm in diameter) were observed from the lower A horizon to the top of the fragipan. Crumb and dispersion index tests indicated that B2 and deeper horizons were highly dispersive. High dispersivity was strongly correlated with high exchangeable sodium percentage (ESP) and low organic carbon content (Laffan and Cutler 1977b).

According to Laffan and Sutherland (1988), untreated severe tunnel gully erosion causes permanent loss of pastoral productivity and periodic flooding and sedimentation due to increased run-off as a result of reduced vegetation cover over the areas affected by tunnel gully erosion. Other problems include: increased difficulty in the control of weeds and rabbits, depressed land values and low aesthetic values.

In order to to investigate erosion control methods, a small farm with an area of approximately 4 ha (now known as the Wither soil conservation reserve) was purchased by the Government. Various methods were used including natural revegetation, plantation forestry, spaced tree planting, pasture improvement, grazing management, contour works and gully infilling using bulldozing equipment. Initial testing was also carried out on the chemical stabilisation of bulldozed areas using agricultural lime, gypsum and hydrated lime (Laffan and Sutherland, 1988).

The infilling of gullies using the "angle-bulldozing" method, followed by revegetation with permanent pasture was found to be the most effective erosion control method on hillslopes with gradients of less than 20° which were not sevrely tunnel gullied. (Laffan and Sutherland, 1988). A bulldozer was used to excavate the eroded hillside at an angle of 30-45° to the horizontal. The excavations were made to a depth at least equal to the depth of the deepest gullies (Laffan and Sutherland, 1988). Following excavation, the area was resown with grass seed. According to Laffan and Sutherland (1988), maintenance is required once every 5 to 10 years to allow recovery of bare areas and to repair sites where new tunnels have formed. Due to a lack of maintenance of the bulldozed slopes, many of the filled in tunnel gully erosion areas are becoming reactivated (Malborough District Council, pers. comm.)

3.4.4 Site Description

The site location is shown in Figure 3.25. Figure 3.26 is a photograph taken from the northern end of the valley in which the sampling site was located. The hillside from where the sampling was carried out is on west side of the valley (the right hand side slope in Fig. 3.26) which is severely affected by tunnel gully erosion. Undisturbed soil profiles (seen in the gully walls) indicated that the tunnel gully erosion occurred in natural soil (as opposed to soil which has been disrupted by angle-bulldozing).

The eastern hillside in Figure 3.26 is an example of a slope that has had its tunnel gully erosion removed by angle-bulldozing. The sub-soil contains a significant amount of gravel and small boulders resulting from the mixing of the loess rich upper layers with the gravel and boulder rich sub-layers.

Figure 3.28 is a soil map with an accompaning aerial photogtaph, showing the distribution of tunnel gully erosion on the east and west slopes. The west slope has an average gradient of about 23°. The most severe tunnel gully erosion (Fig. 3.27) occurs in thick (>2 m) loess colluvium where approximately 90% of the area is affected. Gullies occurred to a maximum depth of 7 m and an average of 3 m. Figure 3.29 is a typical loess colluvium soil profile showing the prominent fragipan and the loess colluvium which forms the parent material of the Wither Silt loam. The upper 3 m are relatively free of gravel, and below 3 m, the gravel content increases downwards to a maximum of about 50%. The boundary between the loess colluvium and the underlying conglomerate is indistinct, but probably occurs at a maximum depth of about 7 m. The maximum boulder size was found to be about 0.5 m.

In the areas covered by thinner (0 - 2 m thick), stonier loess-gravel colluvium, only about 20% of the area was affected by shallow (< 1 m), often partially collapsed tunnel gullies.

Fan deposits resulting from sedimentation from tunnel gully erosion have accumulated at the toe of the main tunnel gully erosion areas to a thickness of about 2 m. Modern erosion is indicated by the existence of recently formed fans (Fig. 3.30).

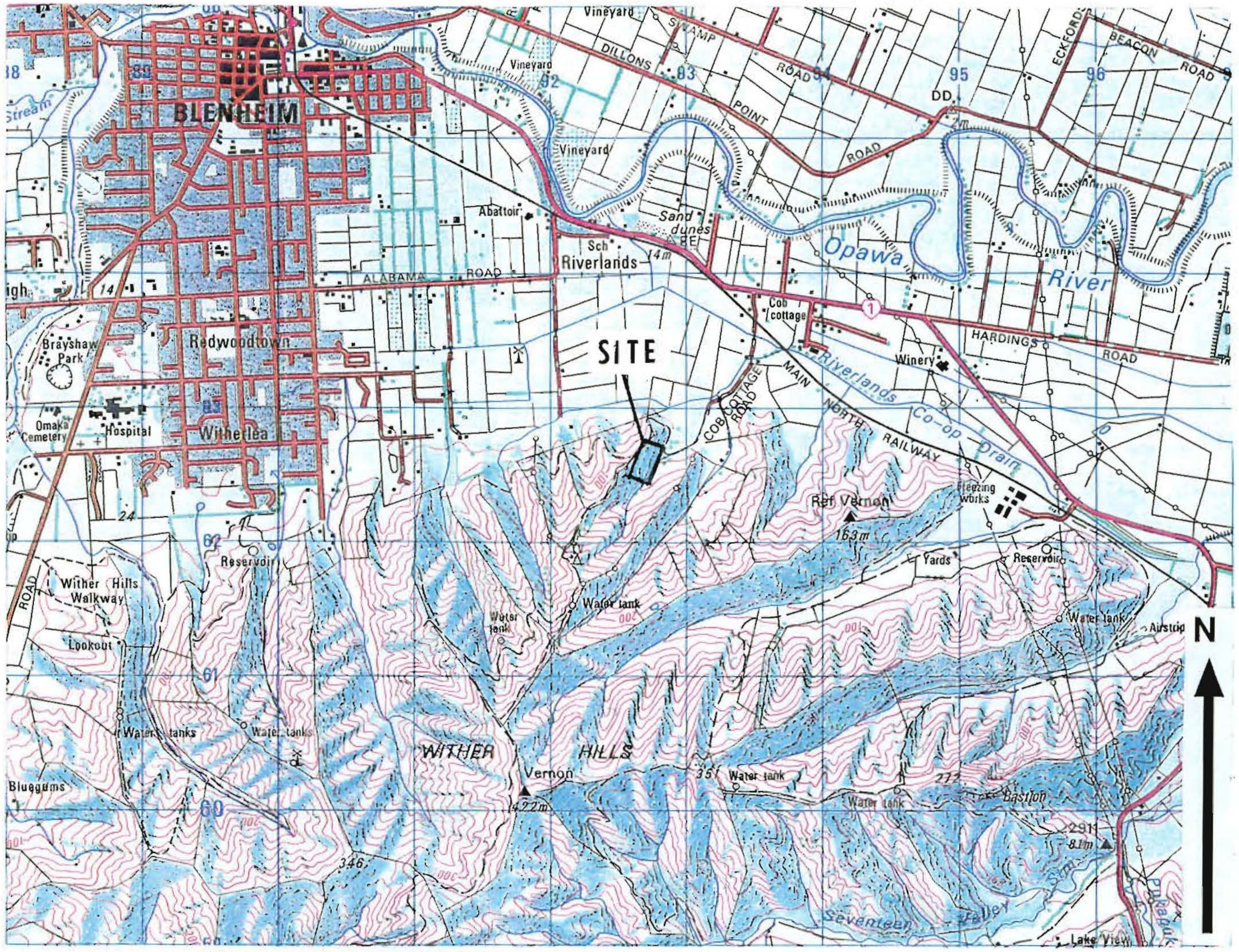


Figure 3.25: The location of the Wither Hills sampling site. Scale: 2 cm = 1 km. Source: NZMS 260, sheet J39.

Figure 3.26: The two sides of the valley in which the sampling site is located. The sampling site is on the right (west) hillslope which is affected by tunnel gully erosion. The left side is free of tunnel gully erosion as a result of the bulldozer treatment method.

Figure 3.27: Severe tunnel gully erosion on the Wither Hills.

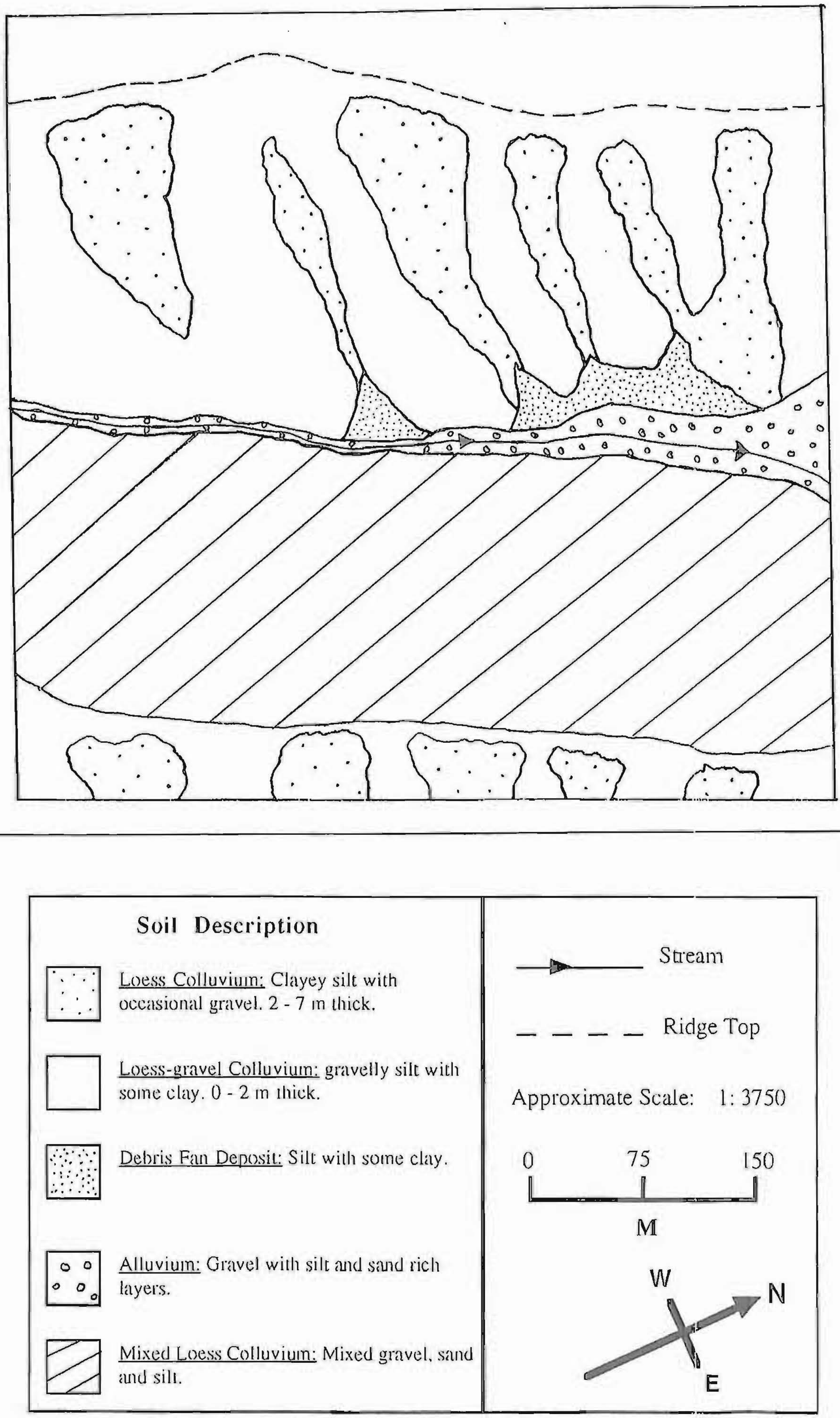
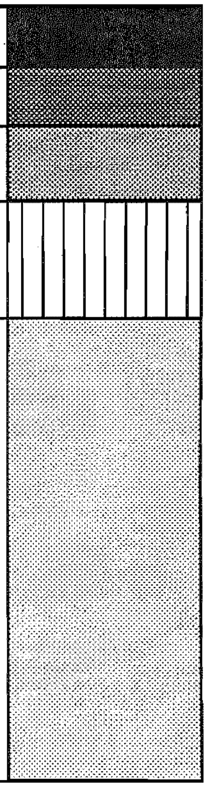


Figure 3.28: Soil map of the sampling site with aerial photograph of the same area showing the extent of tunnel gully erosion.

Figure 3.29: A typical Wither Hills loess colluvium soil profile.

Figure 3.30: Sediment fans resulting from recent gully erosion.



Horizon	cm	Soil Material	Structure and Weathering
A	0–15	Moist, soft, Dark greyish brown clayey silt. Top soil (OL).	Weakly developed medium crumb.
B_1	15–30	As above, but saturated (OL).	Weakly developed fine blocky.
B_2	30–50	Slightly weathered, moist, compact, greyish brown clayey silt with some fine sand with about 20% organics (ML/OL).	Moderately developed medium prismatic. Gley mottling affects about 40% of material
C_x	50–80	Slightly weathered (mottled), dry, very compact, yellowish brown clayey silt with some fine sand. Fragipan (ML).	Moderately developed medium blocky. Gley motling affects about 40% of material.
C	80–200	Slightly weathered, dry, compact, yellowish brown clayey silt with some fine sand with occasional fine gravel. Parent loess-colluvium (ML).	Moderately developed medium blocky.

Figure 3.31: Representitive soil profile of the top 2 metres of Wither Hills loess-colluvium. See Appendix B for an explanation of soil terminology.

Tube samples were extracted from a cutting that was made into the face of one of the gullies. Generally, the soil on the faces of the gullies was very dry and hard. However at the sampling site, the gully face was covered with soil debris so that the face soil was kept moist. Three auger holes provided soil profile information and soil for laboratory tests. The loess colluvium below a depth of about 0.6 m was very dry and the soil often fell out of the auger while it was being pulled out of the hole. As a result the auger holes were only drilled to a depth of 1.5 m. The soil profile which was determined from the augering and inspection of gully walls is shown in Figure 3.31.

3.5 Synthesis

1. There are two major loess deposits on the the Port Hills. Birdlings Flat loess, which is situated in the sub-humid climate zone, has a prominent fragipan and is prone to sub-tunnel gully erosion. Dessication surface cracking due to vegetation removal and exposure to the sun is considered to be an important factor in the tunnel gully erosion process in Birdlings Flat loess. Barrys Bay loess which is not prone to tunnel gully erosion, is situated in the humid climate zone and it does not have a fragipan. The most prominent feature of Barrys Bay loess is a zone of gammate veins which occurs in the B horizon.

2. Most of the loess deposits found on the South Canterbury Downlands, including the Timaru Downs, are free of tunnel gully erosion. However, tunnel gully erosion was identified in two parts of South Canterbury: the upper Pareora River and the hillsides on the western fringe of the Timaru Downs where the Taiko site is located.

3. Previous work on the tunnel gully erosion on the Port and Wither Hills suggests that the fragipan is an important factor in the tunnel gully erosion process. However, Taiko loess-colluvium (which is prone to tunnel gully erosion) does not have a fragipan. This finding suggests that the presence of a fragipan is not a prerequisite for tunnel gully erosion to occur.

4. The loess of the Timaru Downs is situated on rolling hills with very little relief. The loess is unlikely to have been affected by slope movement processes and it is classified as in-situ loess. The loess on the western fringe of the Timaru Downs is situated on steeper hillsides than the Timaru downs. The occurence of clasts of the underlying tertiary

sandstone in samples from the Taiko site suggests and it has been subjected to slope movement, and as a result it is classified as loess colluvium.

5. Subsurface erosion was observed in Timaru loess that has been used as fill material. This shows that in its remoulded form, Timaru loess is potentially erodible even though it is free of tunnel gully erosion in its natural state. It is likely that lack of top soil and grass (which would encourage soil dessication cracks) on the fill material is an important factor in the development of the sub-surface erosion.

6. The Loess at the two tunnel gully erosion free sites: Timaru and Barrys Bay have soil profiles in which gammation veining is a prominent feature. The Port Hills, Wither Hills and Taiko soil profiles are all non gammate.

Chapter 4: Comparison of Geotechnical Properties

4.1 Introduction

In this chapter a comparison is presented of the dispersive and erosive properties of loess soils from the six sites described in Chapter 3. The review given in Chapter 2 showed that no one single test is capable of predicting field erodibility, and therefore a number of different test methods were used. The modified Emerson crumb test, the dispersion % test, and ESP/CEC data were used to determine dispersivity. The quantitative erosion test was used to determine erodibility while the uniaxial expansion test and the slake rate test were used to access slaking. To further characterise and understand the nature of the soils being tested, shear strength, plasticity, permeability, clay mineralogy, bulk density, water content and dry density were also determined.

Previous work carried out on Port Hills loess suggests that loess characteristics from different locations are quite variable. Due to time restrictions, it was only possible to take samples from one site in each of the loess deposits being investigated. Therefore, this project was considered as a pilot study which could indicate areas in which further work would be warranted.

Because the main focus of this project, tunnel gully erosion is essentially a surface process, samples were taken from a maximum soil depth of 2 m. To investigate the change of soil properties with depth, samples were taken from up to three soil horizons.

4.2 Clay Mineralogy

X-ray diffraction methods were used to determine both sand and clay mineralogy. Test procedure and details on how clay mineral percentages were determined are given in Appendix K. All samples were obtained from the C horizon up to a maximum depth of 2 m. Previous work by Laffan (1973) and Miller (1971) has shown that clay mineralogy does not vary significantly with depth, and therefore it was decided that it would not be necessary to determine the clay mineralogy of other horizons.

The X-ray diffraction patterns for each of the six samples are shown in Appendix K. Table 4.1 shows the proportion of the different clay minerals in each of the samples. In all of the samples, a considerable fraction (52-25%) of the clay sized material was composed of non clay minerals (quartz and feldspar). Table 4.2 shows the composition of the soils with the non clay minerals included. Definitions of the terms: "clay minerals" and "clay sized minerals" are given in Appendix K.

The following observations were made about the data in Tables 4.1 and 4.2:

1. Generally speaking, all of the samples are similar in composition and content of clay minerals. In all of the samples, illite is the dominant clay mineral and the second most common clay mineral, was interstratified illite/vermiculite. According to Mclaren and Cameron (1993), as illite clay minerals weather, the Fe^{2+} ions in the structural layers are oxidised to Fe^{3+} ions. This causes a reduction in the negative charge on the layers and results in a loss of K^{+} ions from the interlayers, entry of water and hydrated cations into the interlayer, and an increase in basal spacing. This weathering process is responsible for the formation of the interstratified illite/vermiculite which represent an intermediate stage in the transformation from illite to vermiculite. Therefore, the dominance of illite in the clay mineral fraction is suggestive of a weak weathering regime.

2. A small amount of kaolinite was found in the three Banks Peninsula samples. The two Port Hills samples had considerably higher kaolinite contents than the Barrys Bay sample. Kaolinite either originates from other clay minerals by leaching in a strong weathering regime or is derived directly from the weathering of parent rock (Mclaren and Cameron, 1993). As the soils of the Port Hills exist in a sub-humid climate and are weakly leached it is unlikely that the kaolinite resulted from the alteration of illite. Therefore the kaolinite was probably derived from the weathering of volcanic (basalt) rock which was mixed into the loess by colluvial slope processes. Trangmar (in prep.) also came to the similar conclusion.

3. Quartz and feldspar make up a considerable part of the clay sized mineral fraction. The Wither Hills sample has a non-clay mineral % that is considerably higher than the other samples. It is possible that this is one of the causes of the extreme tunnel gully erosion that occurs on the Wither Hills. The low clay mineral content in the clay fraction would significantly reduce soil cohesion and the soil would as a result become prone to slaking

	% of Clay Minerals			
Site	Illite	Verm-Illite	Kaolinite	Vermiculite
Ahuriri	62	24	11	3
Gebbies	54	27	11	8
Timaru	84	16	-	-
Taiko	74	26	-	-
Wither	71	29	-	-
Barrys	71	27	2	-

Table 4.1: Clay mineralogy of C horizon material. Verm-illite = interstratified vermiculite and illite.

	% of Clay Sized Fraction						
Site	I	V/I	K	V	Q	F	% Clay Min.
Ahuriri	47	18	8	2	19	6	75
Gebbies	38	19	8	6	21	8	71
Timaru	54	10	-	-	24	12	64
Taiko	50	18	-	-	19	13	68
Wither	34	14	-	-	35	17	48
Barrys	48	18	1	-	22	11	67

Table 4.2: Composition of clay sized fraction of C horizon material. I = Illite, V/I = Interstratified Vermiculite and Illite, K = Kaolinite, Q = quartz, F = feldspar.

Site	Horizon	Depth (m)	Sand % 60 - 2000 μm	Silt % 2 - 60 μm	Clay % < 2 μm
Ahuriri	Cx	0.4 - 1	9.5	67.0	23.5
	C	1 - 2	11.0	71.8	17.3
Gebbies	B	0.15 - 0.4	13.7	63.9	22.4
	Cx	0.4 - 0.95	9.1	67.3	23.7
	C	0.95 - 2	10.2	71.0	18.8
Timaru	B2	0.4 - 0.8	3.4	75.6	21.0
	Cx	0.8 - 2	3.7	73.8	22.5
Taiko	B	0.3 - 1.05	14.8	58.6	26.6
	C	1.05 - 2	18.6	58.2	23.2
Wither	B2	0.3 - 0.5	5.8	62.2	32.0
	Cx	0.5 - 0.8	5.8	67.5	26.8
	C	0.8 - 2	5.9	68.5	25.7
Barrys	B1	0.3 - 0.5	8.9	70.3	20.8
	C	1 - 2	9.5	72.7	17.8

Table 4.3: Grain size distribution results.

and erosion.

4.3 Sand and Silt Mineralogy

Owing to time restrictions, only a qualitative estimate of the different proportion of minerals in the sand and coarse silt fraction was carried out using X-ray diffraction analysis. As expected, the sand fraction was largely composed of quartz and albite feldspar. Muscovite was the next most common mineral for all of the other samples except for the Wither Hills sample, which had more orthoclase feldspar than muscovite.

4.4 Grain Size

The results of the grain size analyses carried out using the methods given in Appendix D are shown in Table 4.3 and Figure 4.1. The results are based on one sample per horizon. To ensure that the samples used for grain size analysis were representative of the total sample, the total soil sample was thoroughly mixed before testing. The grain size distribution curves of all the samples are shown in Appendix D.

From the results, the following observations were made:

1. All of the samples are poorly graded. For the C horizon loess (excluding the Taiko sample) medium and coarse silt make up 58-76 % of the soil . According to Pye (1984), loess typically has about 50 - 80 percent silt (2 - 60 μ). Therefore the loess deposits studied in this project have similar grain size characteristics to loess deposits overseas.
2. The Taiko soil had only 50.4% medium and coarse silt and it had a considerably higher sand content: (18.6%) than the other samples. According to Bagnold (1941), only particles finer than about 200 μm are capable of being carried in suspension. Therefore, alot of the sand was probably derived from the underlying Tertiary sandstone as a result of colluvial slope processes.
3. The Timaru sample has a considerably lower sand content (3.7%) than the Banks Peninsula sites (9.5 -11%). The low sand content of Timaru loess is probably a result of the lack of colluvial input due to the fact that located on rolling downland. The three Banks Peninsula soils are located on steeper hills and as a result have an input of colluvial material.

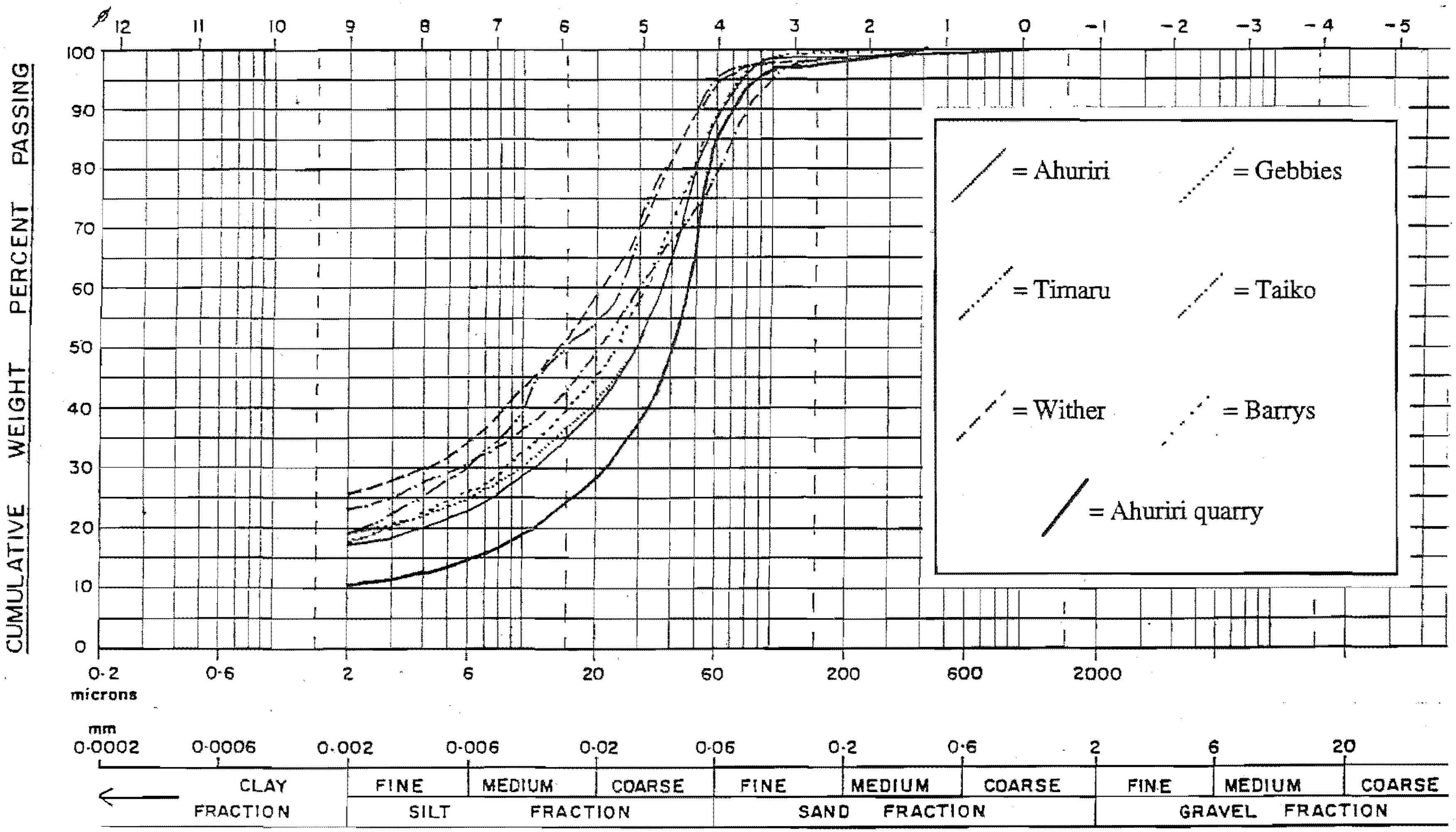


Figure 4.1: Comparison of the grain size distribution of C horizon loess from the six sites.

4. The three Banks Peninsula deposits have very similar grain size characteristics. In C horizon material, Sand % range between 9.5 -11%, silt % range between 71 to 72.7 % and clay % ranges between 17.3 to 18.8%.

5. The Wither hills soil has the highest C horizon clay content. The Wither Hills B_2 horizon also has a very high clay content.

6. Timaru, Taiko and Wither Hills soils have considerably higher clay contents compared to the Banks Peninsula sites.

7. The Gebbies and Ahuriri fragipans (Cx horizons) have considerably higher clay contents than the C horizon material. The Wither fragipan has a slightly higher clay content than the C horizon.

4.5 Plasticity

The standard Atterberg Limit tests (Appendix I) were used to determine soil plasticity and the results are shown in Table 4.4. From the results the following observations can be made:

1. The activities are in the range of 0.19 to 0.47. According to Skempton (1953) inactive clay minerals (including kaolinite) have activities less than 0.75, normal clays (including illite and vermiculite) have activities between 0.75 to 1.25, while active clays (including montmorillinonite) have activities greater than 1.25. Given that Illite and interstratified illite and vermiculite are the dominant clay minerals, it is surprising that the activities are so low. Trangmar (in prep.) attributed the low activity of Port Hills loess to the fact that the clay fraction was dominated by weakly weathered clay minerals. According to Mclaren and Cameron (1993), weakly weathered illite clay minerals have layers which are strongly bonded by interlayer K^+ ions. This bonding causes the illitic clay to have a low swelling potential and as a result a low activity.

2. In a description of the properties of loess from around the world, Bell (1983) stated that the plasticity index of loess typically ranges from 4 to 9. Taiko loess-colluvium with a plasticity index of 11 is the only sample with a plasticity index not in this range. This result is due to the fact that clay mineral activity of the Taiko sample is relatively high (0.47). From the discussion given in point 1. it seems likely that the higher activity is the result of increased weathering/leaching of the Taiko soil.

Site	Depth (m)	Horizon	W %	LL	PL	PI	Activity
Ahuriri	0.2 - 0.4	B	16.1	-	-	-	-
	0.4 - 1	Cx	10.1	23	16	7	-
	1 - 2	C	11.5	22	18	4	0.23
Gebbies	0.15 - 0.4	B	18.6	-	-	-	-
	0.4 - 0.95	Cx	15.3	25	16	9	-
	1-2	C	11.5	22	17	5	0.27
Timaru	0.4-0.8	B2	17.4	-	-	-	-
	0.8-2.0	Cx	15.8	23	15	8	0.36
Taiko	0.3 - 0.75	B	16.4	27	15	12	-
	0.75 - 2.0	C	13.2	26	15	11	0.47
Wither	0.15 - 0.3	B1	21.1	-	-	-	-
	0.3 - 0.5	B2	18.8	-	-	-	-
	0.5 - 0.8	Cx	12.9	22	16	6	-
	0.8 - 2	C	11.8	20	15	5	0.19
Barrys	0.3-0.5	B1	19.5	-	-	-	-
	0.5-1.0	B2	21.4	-	-	-	-
	1-1.4	C	21.5	24	20	4	0.23

Table 4.4: Atterberg limit results.

Site	Cohesion (kPa)	Ø
Ahuriri Quarry	0	39°
Gebbies Valley	3	40°
Timaru	7	28°
Taiko	4	34.5°
Wither Hills	7	35°
Barrys Bay	10	36°

Table 4.5: Drained, remoulded shear strength characteristics. Ø = angle of internal friction.

3. Wither Hills loess has the highest clay content (25.7%), and the lowest plasticity index. As a result the activity is very low (0.19). Given that the clay mineralogy of Wither Hills loess is essentially the same as the other loess deposits, it is surprising that the activity is so low. The low activity is probably a result of the fact that quartz and feldspar (non clay minerals which by definition have zero activity) make up approximately 52% of the clay sized fraction. The other samples have only 36 -25% non clay minerals in the clay sized fraction.

4.6 Shear Strength

Drained, saturated, shear strength tests were carried out according to the method given in Appendix J. Except for the Ahuriri site, all samples were taken from the C horizon. At the Ahuriri site, the material was taken from a bulk sample from the Ahuriri quarry which was representative of the soil in the quarry to a depth of about 16 m. Test material from the other sites was collected from auger holes. The samples were then recompacted (at approximately optimum moisture content) in a Proctor mould. For each site, three tests were carried out at normal stresses of 50.6, 101.19 and 151.79 kPa and a shearing rate of 0.0032 mm/min was used.

The shearing rate was estimated from Chandler and Rodgers (1980) who suggested a rate of between 0.0005 to 0.0009 mm/min for heavy clays. Given that loess (basically a silt) has a considerably higher permeability than clay rich material it was decided that a rate of 0.0032 mm/min would be slow enough for drained testing. At this rate, it took approximately 24 hours for sample failure to occur.

Direct shear test data was collected in the form of shear strength versus displacement graphs of which Figure 4.2 is a typical example. All of the shear strength versus displacement graphs are shown in Appendix J. The cohesion and angle of internal friction results are summarised in Table 4.5. The shear stress versus normal stress graphs from which the shear strength characteristics are determined are shown in Appendix J.

From the results the following observations were made:

1. Cohesion values were found to be in the range of 0-10 kPa. The correlation between clay content and cohesion was moderate with $r = 0.53$ (Fig.4.3). This is in agreement with

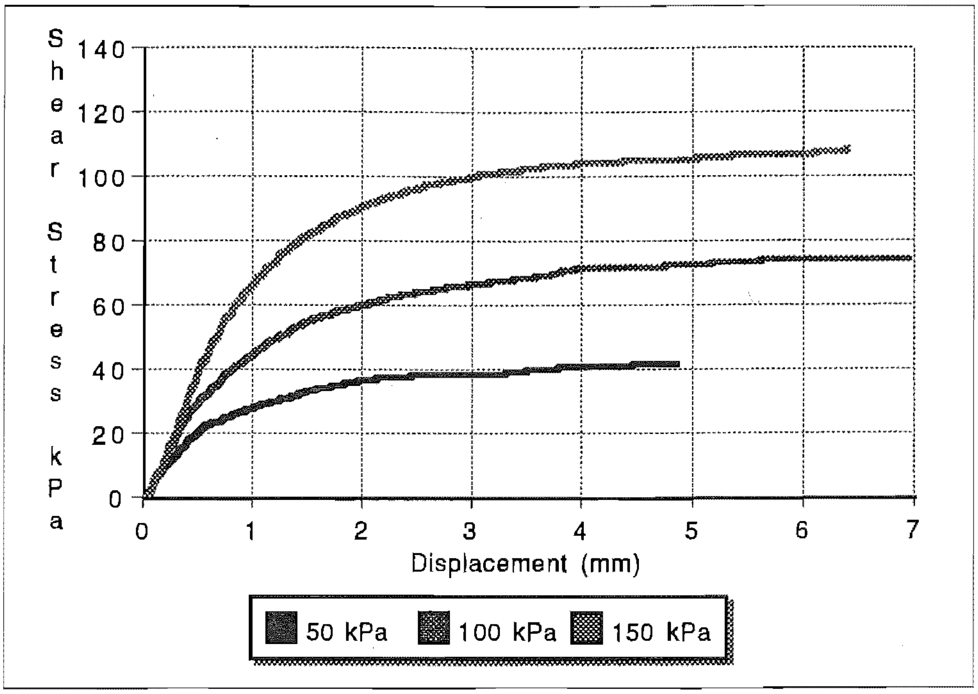


Figure 4.2: Shear stress versus displacement relationship for Wither Hills loess tested at normal stress levels of 50, 100 and 150 kPa.

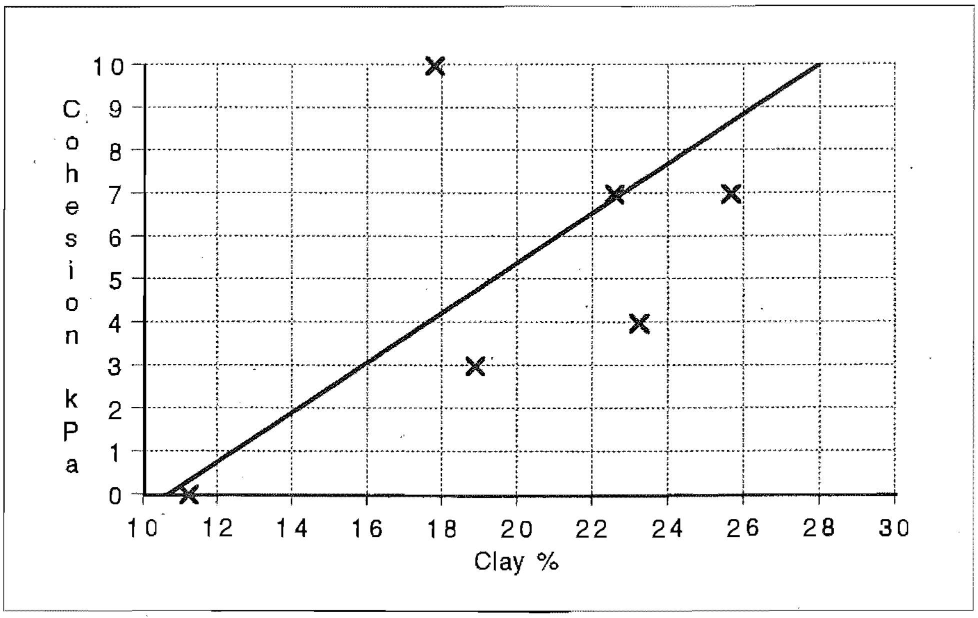


Figure 4.3: Relationship between clay % and drained cohesion. r = 0.53.

the generally accepted fact that clay minerals are the main source of a soils cohesive strength.

2. Friction angles were found to be in the range of 28-40°. In an overview of the geotechnical properties of loess Bell (1983) stated that loess typically has a friction angle in the range of 30-34°. Therefore it appears that the loess samples studied in this project display a relatively large range of friction angles. A moderate ($r = 0.47$) relationship was found to exist between sand % and friction angle (Fig. 4.4).

3. On the shear stress versus displacement graphs (of which Figure 4.2 is a typical example) there was no marked point of failure and as a result, residual strength was very similar to peak strength. Similar results were also obtained by Goldwater (1990).

4.7 Permeability

Falling head permeability testing was carried out on remoulded samples by the method given in Appendix E. The test results are given in Table 4.6. One permeability test per sample was carried out. To ensure saturation, the samples were left to soak in proctor moulds for approximately 3 days prior to testing.

From the results, the following observations were made:

1. Remoulded permeabilities were found to be in the range of 1.41×10^{-8} m/s to 1.56×10^{-9}. According to Bell (1983) permeabilities in this range are typical of dense clayey silt. According to Birrel and Packard (1953) the undisturbed permeability of Port Hills loess is about 1.5×10^{-7} m/s. These results show that remoulding significantly reduces permeability. In its undisturbed condition, loess is typically porous as a result of many root and worm holes which penetrate the soil material. The mode of deposition of loess i.e by settlement from suspension, also increases porosity. A permeability/porosity decrease and a density increase is caused when the soil is remoulded and recompcated.

2. A strong negative correlation ($r = -0.79$) between clay content and permeability suggests that as clay content increases, permeability decreases (Fig. 4.5). This is in agreement with the generally accepted fact that clay reduces permeability.

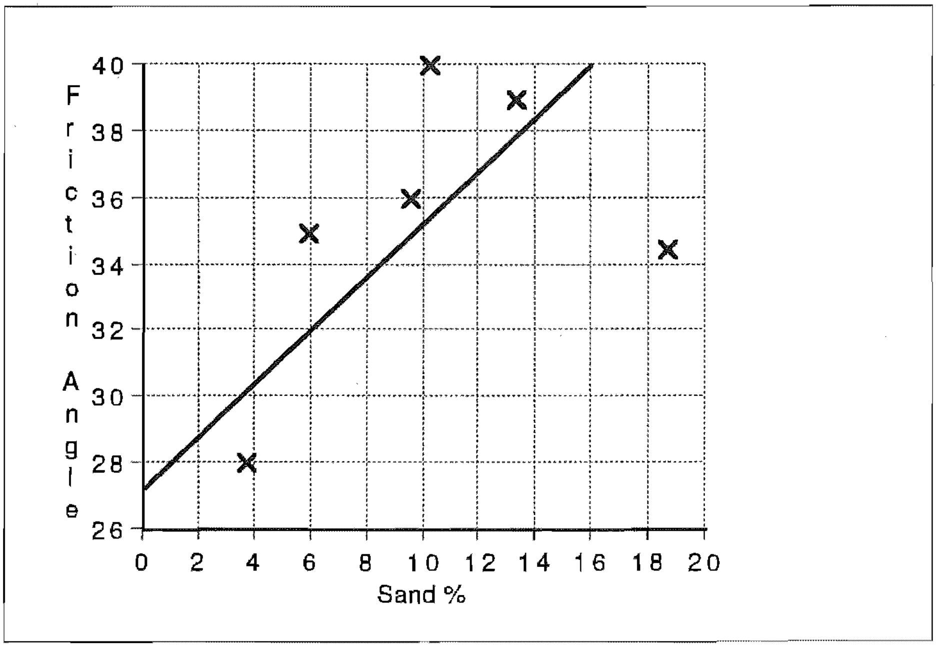


Figure 4.4: Relationship between sand % and friction angle. r = 0.47.

Site	Permeability (m/s)	Clay %
Ahuriri Quarry	1.4 x 10-8	11.2
Ahuriri	5.6 x 10-9	17.3
Gebbies	2.0 x 10-9	18.8
Timaru	1.6 x 10-9	22.5
Taiko	2.3 x 10-9	23.2
Wither Hills	4.6 x 10-9	25.7
Barrys Bay	9.1 x 10-9	17.8

Table 4.6: Permeability test Results.

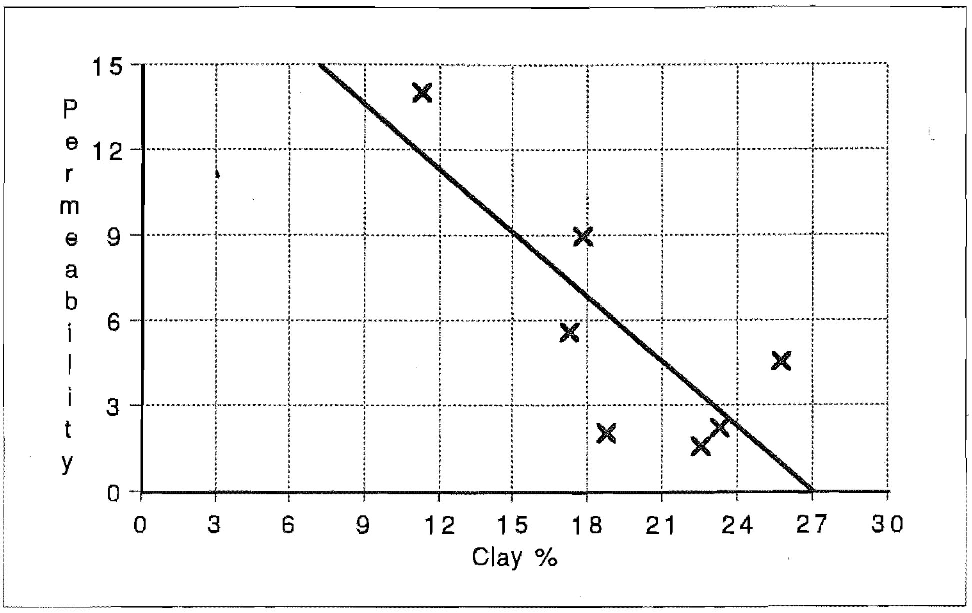


Figure 4.5: Relationship between clay content and permeability (in m/s $\times 10^{-9}$). r = - 0.79.

Site	Horizon	Crumb Grade	Dispersion %	CEC	ESP
Ahuriri	B	2	-	-	-
	Cx	2.5	49	-	-
	C	2.5	85	10.4	31.2
Gebbies	B	2	37	-	-
	Cx	3	64	-	-
	C	3	77	11.0	29.7
Timaru	B2	3	76	-	-
	Cx	3.5	79	9.6	19
Taiko	B2	3.5	78	-	-
	C	3.5	86	12.2	10.3
Wither	B2	3.5	75	-	-
	Cx	3.5	88	-	-
	C	4	86	12.2	25.2
Barrys	B1	2	42	-	-
	C	3	781	7.0	5.3

Table 4.7: Dispersivity test results. ESP (exchangeable sodium percentage) and CEC (cation exchange capacity) concentration in me/100g.

4.8 Dispersivity

After reviewing the different dispersion test methods (Chapter 2) it was decided that the modified Emerson crumb test and the modified British standards dispersion test (which is closely related to the SCS dispersion test) were the most convenient ways of determining clay mineral dispersion. For comparative reasons, the ESP (exchangeable sodium percentage) of C horizon material was also determined. Test methods are given in Appendix F. All tests were carried out on soil at field moisture content.

As a result of time restrictions, dispersion % results are based on one test for each soil. Therefore it was not possible to determine the reproducibility of the test results. As shown in Chapter 2 there are are contrasting opinions as to the dispersion % over which a soil is described as being "dispersive". In this project, the critical dispersion value for silts with low plasticities of 50 % determined by Heinzen and Arulanandan (1977) will be adopted. The crumb test results results shown in Table 4.7 are based on crumb tests which were carried out on five separate crumbs of soil. According to Sherard (1976b) a crumb grade of 1 indicates non dispersion, 2 indicates slight dispersion, 3 indicates strong dispersion and 4 indicates extreme dispersion.

Previous work has shown that the amount of exchangeable sodium on the exchange complex of clay minerals (ESP) has a major influence on dispersion. In Chapter 2 it was found that the critical value of ESP required for dispersion has been quoted by various authors as being in the range of 6 - 10%. ESP and CEC values of C horizon soil from each of the sites are also shown in Table 4.7. All testing was carried out by Soil Fertility Service staff (N.Z Pastoral Agriculture Research Institute Limited, Invermay).

From the results, the following observations were made:

1. In general, clay mineral dispersion increases with soil profile depth. The increase of dispersion tendency with depth is attributed to a decrease of organic matter (in the form of humus) with depth. An explanation of why organic material reduces dispersion tendency has been given in section 2.2.1.

The soil profile descriptions given in Chapter 3 show that the B2 horizons at the Timaru, Taiko and Wither Hills sites had considerably less organic material, than the B and B1 horizons identified at the Ahuriri, Gebbies and Barrys Bay sites. Given this, it is not surprising that the B2 horizons had considerably higher dispersivities than the B and

B1 horizon material. It is interesting to note that the Wither Hills B2 horizon which was described as Laffan and Cutler (1977b) as being the horizon in which tunnel gully erosion on the Wither Hills initiates has the same dispersivity and similar crumb and ESP values as the B2 horizon at the non tunnel gullied Timaru site.

2. The crumb test indicated that all of the samples are at least moderately dispersive. Wither Hills loess is the only sample to have a crumb class of 4. This is significant given that Wither Hills loess is the sample most susceptible to tunnel gully erosion. Both the C_x and B_2 and C_x horizons in Wither Hills loess also have crumb classes which indicate high dispersivity. Timaru and Barrys Bay loess are also highly dispersive. This is surprising given the non-susceptibility of Timaru and Barrys Bay loess to tunnel gully erosion. Ahuriri and Gebbies Valley loess were also found to be dispersive, although both had slightly lower crumb grades than the two non tunnel gullied samples.

3. According to the dispersion test results, all of the C horizon soils are strongly dispersive, with dispersion % in the range of (77-86%).

4. In general, the two non tunnel-gully affected soils (Barrys Bay and Timaru) do not seem to be any less dispersive than the soils which are affected by tunnel gully erosion. This result suggest that factors other than just clay mineral dispersion play an important part in the tunnel gully erosion process.

5. According to the 6-10% ESP boundary for dispersion, all of the samples except for the Barrys Bay sample would be classified as being dispersive. The fact that the three sites most susceptible to tunnel gully erosion (Ahuriri, Gebbies and Withers) have the three highest ESP values suggests that exchangeable sodium content is a factor in the tunnel gully erosion process. This finding is also supported by the fact that the Barrys Bay soil, which is not prone to sub-surface erosion, has the lowest ESP value. However, the relatively high ESP of the non tunnel gullied Timaru loess suggests that further testing is required before any definite conclusions can be made.

According to previous work, ESP is one of the strongest controls on dispersion. Given this, there sould be a strong relationship between ESP and the results of the two dispersion tests. However, the correlation between % dispersion and ESP was very low ($r = -0.07$) as was the relationship between crumb class and ESP ($r = -0.22$). This result suggests that other factors apart from ESP have influences on the results of the two dispersion tests. Previous work has shown that pH, organic carbon content, clay mineralogy and water content also have an affect on dispersivity.

6. Using results from all soil profiles, there was found to be a reasonably strong relationship (r = 0.72) between crumb class and % dispersion (Fig. 4.6). This is an expected result given that both tests measure the same characteristic (dispersivity).

4.9 Erodibility

A modified version of the quantitative pinhole test which was developed by Schafer and Trangmar (1981) was used to determine erodibility (Appendix G). In the quantitative erosion test, an "erosion index", which is equal to the volume of eroded soil, is used as an indicator of erodibility. Schafer and Trangmar (1981) arbitrarily considered that soils exhibiting erosion indices greater than 1 were "erodible".

The results shown in Table 4.8 represent average test result values. Complete test data is given in Appendix G. All testing was carried out at the University of Canterbury Engineering Geology laboratory and tap water was used as the eroding fluid.

Sherard et. al. (1976a) found that soils that were dispersive in the pinhole test when distilled water was used as the eroding fluid were non dispersive when river water with small amounts (2-20 g/m^3) of Ca^{2+} was used as the eroding fluid. It is the opinion of the author that Christchurch tap water has a similar affect on soil dispersion and as a result, clay mineral dispersion is unlikely to have any significant affect on pinhole erodibility when Christchurch tap water is used as the eroding medium. An explanation for this statement is given below.

Crumb tests indicated that soils which were dispersive in distilled water were non-dispersive in the tap water which is used for pinhole testing. For instance, Timaru C horizon material was dispersive (crumb grade = 3.5) in distilled water; in tap water it was only slightly dispersive (crumb grade = 1.5). As discussed in Chapter 2, sodium ions tend to encourage dispersion while calcium and other divalent ions such as magnesium tend to inhibit dispersion. Table 4.9 shows that calcium is the dominant ion in Christchurch tap water, and that it occurs at similar concentrations to the non dispersive river water given in the example above. Therefore, it seems that calcium ions are the cause of the non dispersion of soils in tap water. Pinhole tests using distilled water as the eroding fluid were carried out on two soils and compared to pinhole tests using tap water to determine the extent to which dispersion plays a part in the erosion process of the two samples. If

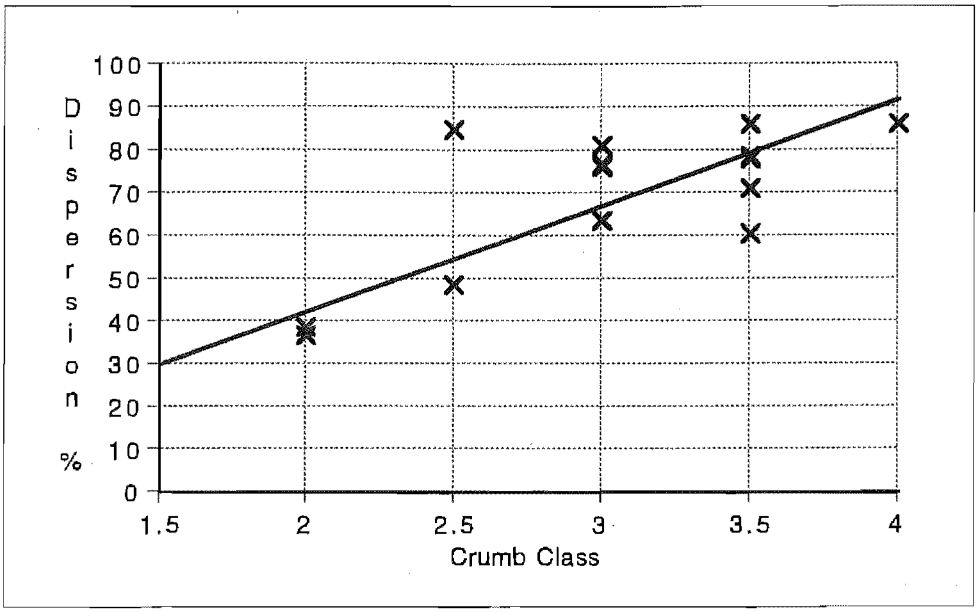


Figure 4.6: Relationship between Crumb class and Dispersion %. r = 0.72

Site	Horizon	% Erosion (tap water)	% Erosion (distilled water)	Water Content	Clay Content (%)
Ahuriri	C	23.6	20.4	8.1	17.3
Gebbies Valley	B	1.7	-	20.0	22.4
	Cx	11.9	-	6.3	23.7
	C	24.9	-	11.2	18.8
Timaru	B2	1.6	-	14.0	21
	Cx	4.5	-	11.2	22.5
Taiko	B2	0.2	-	15.1	26.6
	C	0.2	1.6	15.4	23.2
Wither Hills	B2	0.2	-	10.4	32
	Cx	1	-	12.6	26.8
	C	11.8	-	8.2	25.7
Barrys Bay	B2	0.3	-	14.7	20.8
	C	0.3	-	15.4	17.8

Table 4.8: Pinhole erodibility test results.

dispersion plays a significant part in the erosion process, then the erosion indices with distilled water as the eroding fluid will be higher than when tap water is used as the eroding fluid.

Calcium (Ca^{2+})	14
Magnesium (Mg^{+})	2
Potassium (K^{+})	1
Sodium (Na^{+})	6

Table 4.9: Typical cation concentration (in g/m^3) of Christchurch water (after Bathurst, 1989).

From the results shown in Table 4.8, the following observations were made:

1. According to Schafer and Trangmar's definition of erodibility (given in the introduction of this section), all of the C horizon samples except for Barrys Bay and Taiko are erodible. The low erodibility of the Barrys Bay sample is in accordance with field erodibility. The high erodibility of the Timaru sample is surprising given the fact that Timaru loess is essentially free of tunnel gully erosion. As shown in Chapter 3, loess fill material at the Timaru Harbour board quarry is affected by extreme sub-surface erosion. This finding indicates that when the natural structure of Timaru loess is disrupted, it is in fact an erodible material.
2. Erodibility increases with soil profile depth. The increased organic matter content in the upper soil layers is a probable reason for this relationship: soil organic matter has a binding affect which reduces dispersivity and erodibility (see Chapter 2).
3. Distilled water makes a significant difference to the erodibility of the Taiko sample. Distilled erodibility (1.58) is about 9 times the tap water erodibility (0.17). (NB: according to Schafer and Trangmar, 1981, differences in erodibility are best assessed in terms of ratios. Erosion indices of 1 and 10 represent a much greater qualitative difference of behaviour than erosion indices of 10 and 20. A ten time increase in the amount of eroded material is much more significant than a 2 times increase in the amount of eroded soil). This result is suggestive that Clay mineral dispersion plays an important part in the

erodibility of Taiko loess. In contrast, the distilled water erodibility of Ahuriri loess is only about 1.08 times the tap water erodibility. It appears that dispersion plays a much smaller in determining the extent of erodibility of Ahuriri loess as compared to Taiko loess.

The differences in erodibility characteristics between Taiko and Ahuriri loess are probably due to grain size characteristics. The Taiko sample is relatively clay rich compared to the Ahuriri sample. The slightly higher clay content in Taiko loess means that the soil is more cohesive, and as a result the silt grains are bound together more strongly and the soil is more resistive to erosion in tap water. However, as has been showed by the dispersion tests, the clay minerals in both soils are dispersive, and as a result, pinhole erosion increases when distilled water is used as the eroding fluid. Distilled water seems to have a considerably reduced affect on the Ahuriri sample as compared to the Taiko sample. The interpretation is made that the Ahuriri sample is so prone to physical erosion that the grains are eroded too quickly for clay mineral dispersion to have any effect on the erodibility of the soil. In the Taiko soil, clay mineral dispersion has an affect on erodibility because erosion by physical means is considerably reduced.

4. The relatively high erodibility of Wither Hills loess may be a result of the fact that a significant proportion of the particles in the clay grain size range are non clay minerals (quartz and feldspar). This would considerably reduce cohesion and as a result the soil would be more susceptible to sub-surface erosion.

4.10 Slaking

Two tests were used to determine slaking properties: the uniaxial expansion test and the quantitative slaking test which was developed towards the end of the testing programme. The results are shown in Table 4.10. Typical uniaxial expansion against time graphs of the C horizon samples are shown in Figure 4.7. The uniaxial expansion against time graphs for all the tests that were carried out are shown in Appendix H. Quantitative slake test results were derived from only one test per sample, test data is given in Appendix H.

In the uniaxial expansion test, a confined ring of dry soil is immersed in water and the vertical expansion (as measured by a transducer) is used as an indication of slaking potential. According to Yetton (1986) the clay mineral swelling in Port Hills loess only accounts for a small part of the observed expansion, most of the expansion is the result of

Site	Horizon	Uniaxial Expansion (%)	Slake Rate (undisturbed) (g/min)	Clay %	Dry Density (t/m3)
Ahuriri	Cx	4.2	-	23.5	1750
	C	15.2	-	17.3	1550
Gebbies	B	6.3	1	22.4	1570
	Cx	11.7	-	23.7	1670
	C	15.3	9.4	18.8	1590
Timaru	B2	8.5	1.4	21.0	1790
	Cx	3.9	2	22.5	1830
Taiko	B2	7.6	-	26.6	1730
	C	13.1	-	23.2	1820
Wither	B2	3.1	-	32.0	1760
	Cx	2.4	-	26.8	1650
	C	10.1	-	25.7	1660
Barrys Bay	B2	6.9	3.2	20.8	1630
	C	16.8	14.64	17.8	1650

Table 4.10: Slaking test results.

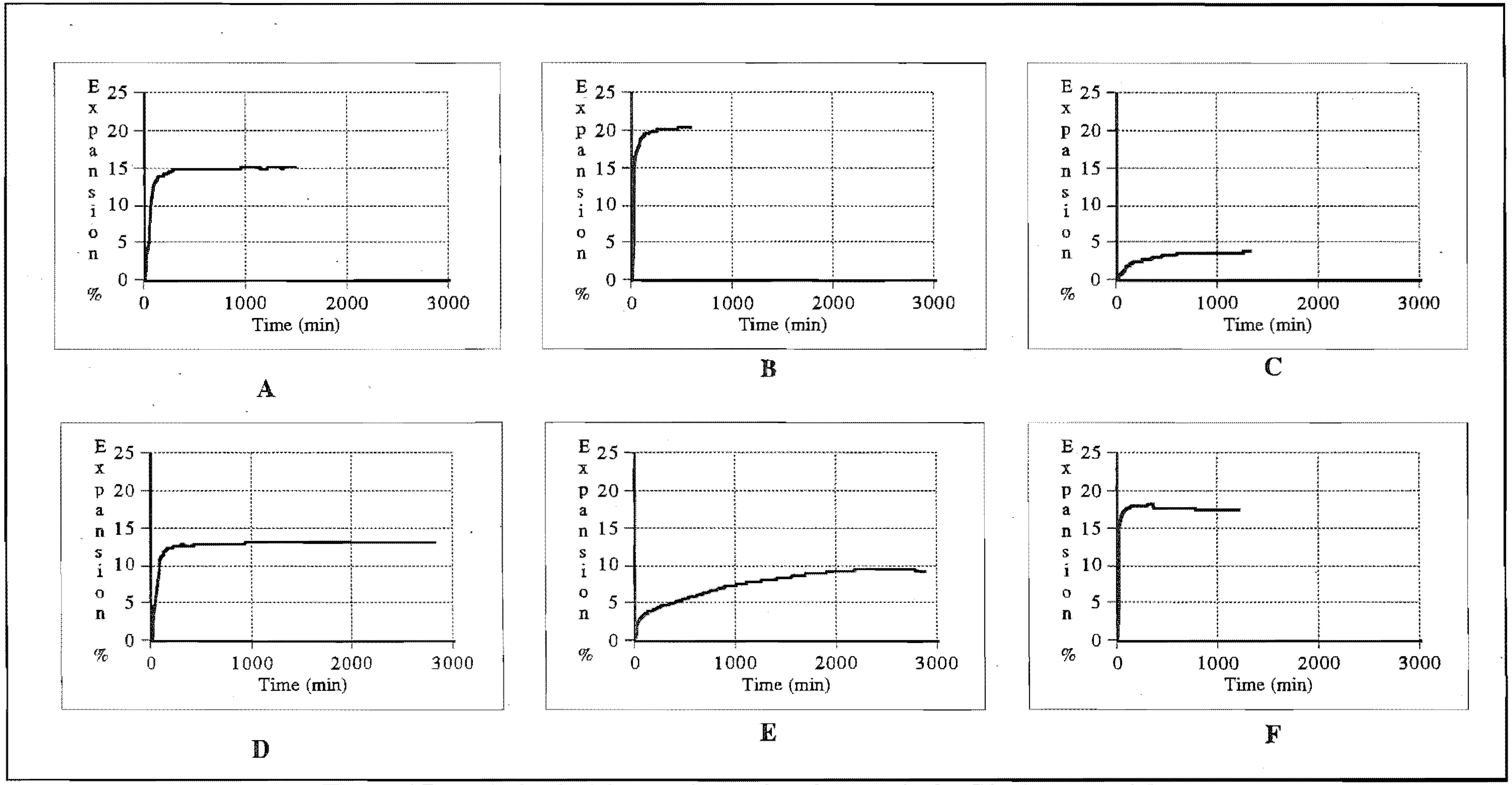


Figure 4.7: Typical uniaxial expansion against time graphs for C horizon material from the six sites. A = Ahuriri, B = Gebbies, C = Timaru, D = Taiko, E = Wither Hills, F = Barrys Bay.

the positive air pressure caused by the in filling of soil voids by water. The increase in air pressure in voids is the most important factor resulting in slaking. Therefore, it is believed that for loessial soils with relatively low clay contents, the uniaxial expansion test measures slaking potential rather clay mineral swelling.

In the quantitative slaking test, slaking is directly measured by measuring the rate of sample disintegration by attaching the sample to the base of a scale. All tests were carried out on undisturbed samples obtained from 35.5 mm diameter core samples that were obtained by the method given in Appendix A. To negate the influence of pore water on the extent of slaking all tests were carried out on air dried samples.

The following observations were made about the results:

1. In general, slaking potential seems to increase with depth. The lower slaking potential of the upper horizons is probably a result of the higher organic content in these layers which acts to bind the particles together and increase resistance to expansion. Also, most of the B horizons have higher clay contents than the deeper layers. Yetton (1986) found that clay rich loess samples tended to be less prone to slaking as a result of increased cohesion.

2. Theory suggests that porosity (which is directly related to dry density) has an effect on the degree of slaking. A lower dry density/higher porosity means that water can more easily penetrate into a soil and as a result cause a higher degree of slaking. A moderately strong inverse relationship ($r = -0.68$) was found between uniaxial expansion and dry density suggests that an decrease in dry density results in an increase in susceptibility to slaking (Fig. 4.8).

3. A moderately strong inverse relationship ($r = -0.65$) was found between between clay % and uniaxial expansion was also determined (Fig. 4.9). This is in agreement with the findings of Yetton (1986) who found that clay content reduced susceptibility to slaking.

4. A strong exception to the correlations given in observations 2 and 3 is the Taiko sample, which has a relatively high uniaxial expansion yet has both a high dry density and a high clay content.

5. The Timaru Cx horizon has a considerably lower uniaxial expansion than horizons at equivalent depths in other deposits. The low uniaxial expansion of Timaru loess is probably the result of its relatively high dry density, low porosity and reasonsably high clay content. The limited quantitative slaking test results also suggest that Timaru Cx loess has a very low slaking potential.

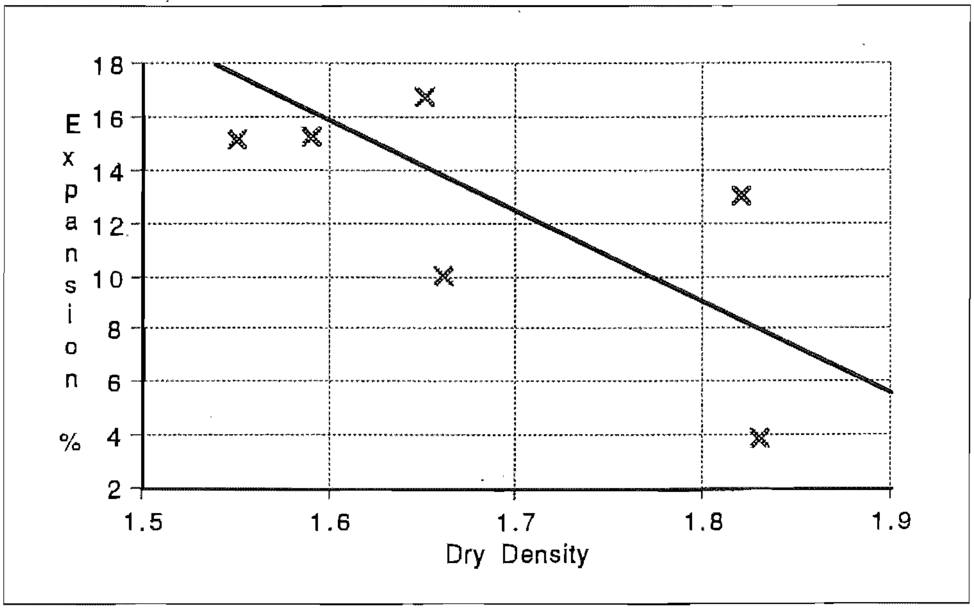


Fig 4.8: The relationship between uniaxial expansion and dry density (kg / m^3).
r = - 0.68.

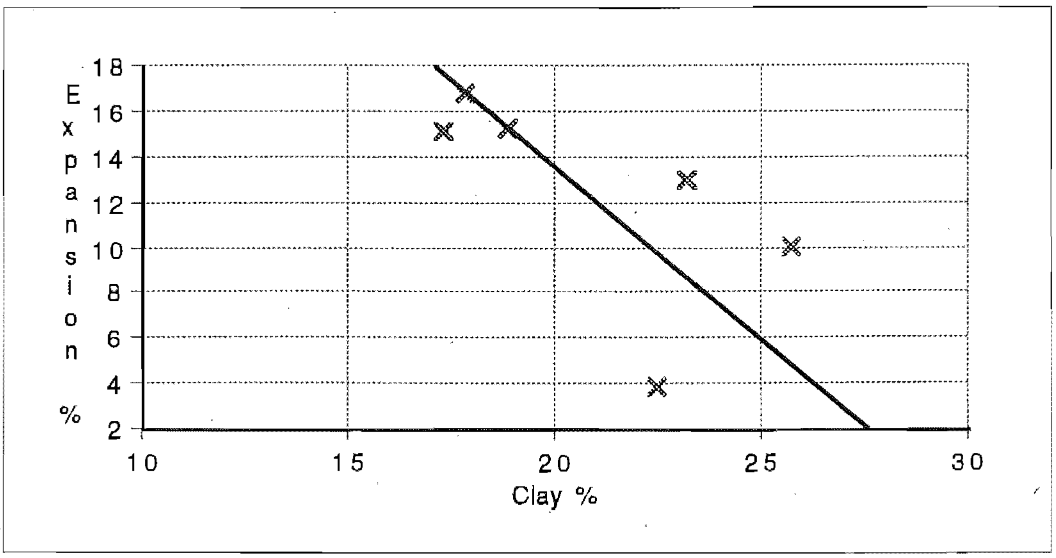


Figure 4.9: The relationship between uniaxial expansion and clay %. r = -0.65.

6. The Banks Peninsula samples all have very high uniaxial expansions resulting from the relatively low dry densities and low clay contents. Barrys Bay loess, a non-tunnel gullied soil, has the highest uniaxial expansion. The limited quantitative slake test results also suggest that Barrys Bay loess is the soil most prone to slaking. The slake rate of Barrys Bay loess is considerably higher than any of the other samples which were tested. Given that the density and clay content of Barrys Bay loess is similar to the other deposits it is difficult to explain the very high rate of slaking.

4.11 Synthesis

1. All of the samples are similar in composition and content of clay minerals. Illite and Interstratified illite/vermiculite clay were the dominant clay minerals. Non clay minerals made up between 25 to 52% of the clay sized fraction. The high non clay mineral content in the clay fraction is a possible cause for the low degree of activity which is observed in tthe loess deposits which were sampled. Wither Hills loess had by far the highest non clay mineral content in its clay sized fraction. This may be a contributing factor to the high erodibility of Wither Hills loess.

2. Banks Peninsula loess has a considerably coarser texture than loess from the Timaru Downs and the Wither Hills. Clay contents for Banks Peninsula, Timaru Downs and Wither Hills C horizon loess were found to be: 17.3 - 18.8%, 22.5 - 23.2 % and 25.7 % respectively.

3. Remoulded effective cohesion values were found to be in the range of 0 - 10 kPa. Angle of internal friction values were found to be in the range of 28 - 40°. This is a large range given that the samples have similar grain size characteristics.

4. Test results indicate that all of the C horizons from the different sites are dispersive. In general, the two non tunnel-gully affected soils (Barrys Bay and Timaru) do not seem to be any less dispersive than the soils which are affected by tunnel gully erosion. This result suggests that factors other than clay mineral dispersion play important roles in the development of tunnel gully erosion.

5. All of the soils, except for the Barrys Bay site have exchangeable sodium percentages which suggest that the soils are dispersive. The three soils most prone to subsurface erosion have the highest ESP's and one of the soils not prone to tunnel gully erosion has the lowest ESP. These results are suggestive of a correlation between ESP and field erodibility.

6. The three Banks Peninsula samples show the highest degree of slaking, while Timaru loess does not seem to be prone to slaking. Clay content and dry density were shown to be important factors in the slaking process.

7. The Gebbies and Ahuriri samples are considerably more erodible than the other samples. The low resistance to erodibility of these samples is probably due to the fact that they have little cohesion due to low clay contents. An exception to this finding, is the Barrys Bay sample which also has a relatively low clay content but is essentially non-erodible in the pinhole test.

8. For clay rich soils such as the Taiko sample, clay mineral dispersion plays an important part in determining the extent of erodibility. For clay poor soils such as the Ahuriri sample, clay mineral dispersion plays an insignificant part in determining the extent of erodibility.

9. In general, laboratory test results did not correlate fully with field erodibility. The two non tunnel gullied soils exhibited some characteristics which suggested that they should be prone to tunnel gully erosion. For instance, the Barrys Bay soil had very high uniaxial expansion and was also dispersive. The Timaru soil was dispersive, and was also erodible as indicated by the pinhole test. The lack of correlation between laboratory test data and field erodibility suggests that other factors such as climate, soil profile characteristics and land use are important factors in the tunnel gully erosion process in the loesial soils of the South Island.

Chapter 5: Chemical Stabilisation Studies

5.1 Introduction

Both quicklime (CaO) and hydrated lime have been used to stabilise Port Hills loess, although the latter is more commonly used because it is a much safer chemical to handle and store. Endurazyme is a recently developed enzyme product which is mainly used for road stabilisation in Australia. In this chapter, a comparison of the stabilisation affects of quicklime and Endurazyme will be carried out.

Section 5.2 details an investigation into the quicklime stabilisation of loess from the Ahuriri quarry (see Figure 3.3 for location). This work was carried out under contract to Fulton Hogan to determine the properties of 2.5% quicklime stabilised Ahuriri quarry loess in order to determine its suitability as a fill material for a small earth dam which is proposed, as part of the development of a Port Hills subdivision.

In section 5.3 the stabilising effect of Endurazyme is investigated. Also, possibility of using a combination of quicklime and Endurazyme for stabilisation will also be investigated. Some data from section 5.2 will be used to compare the stabilising properties of Endurazyme and quicklime. The methods of all of the tests carried out in this section are given in the relevent Appendices.

5.2 Quicklime Stabilisation

5.2.1 Reaction Mechanism

Quicklime (CaO) is prepared by heating calcium carbonate (limestone) in Kilns until carbon dioxide is driven off. The calcium oxide discharged from the kilm is lumpy and has a high heat of hydration which makes it difficult to store and quite dangerous to handle. As a result, the hydrated form of quicklime: $Ca(OH)_2$ which is usually referred to as hydrated lime, is more commonly used for soil stabilisation (Ingles and Metcalf, 1973).

Reaction mechanisms have been attributed (Diamond and Kinter, 1965; Gillott,

1968) to one or more of: clay mineral flocculation by the replacement of exchangeable cations by Ca^{2+}, carbonation of atmospheric CO_2 to form calcium carbonate, and the formation of a water soluble gel of hydrated calcium aluminates and silicates which cement and bond the clay particles together.

5.2.2 Previous work

Since 1978 much work has been carried out on the chemical stabilisation of Port Hills loess (Table 5.1) and with the exception of gypsum all of the chemicals have been found to be effective. An informative review of some of the early work is given by Bell et. al. (1986). Table 5.2 summarises the work carried out by Tehrani (1988) on the quicklime stabilisation of loess from Whaka terrace (see Figure 3.3 for location). Tehrani found that the stabilising effects of quicklime and hydrated lime were very similar. Table 5.2 shows that quicklime: a) Increases erodibility resistance; b) Makes the soil non dispersive; c) Improves resistance to slaking; d) Reduces swelling; e) Increases Strength; f) Increases optimum moisture content; g) Decreases maximum dry density; h) Increases permeability.

Author (s)	Chemical(s)	Location (see Fig. 3.3)
Evans (1978)	Phosphoric Acid, Hydrated Lime	Glenelg spur
Evans and Bell (1981)	Phosphoric Acid, Hydrated Lime	Glenelg spur
Schafer and Trangmar (1981)	Phosphoric Acid, Hydrated Lime	Scarborough
Yetton (1986)	Hydrated Lime	Charteris Bay
Glassey (1986)	Hydrated Lime	Westmoreland
Tehrani (1988)	Hydrated Lime, Quicklime, Gypsum, Cement, Gypsum + Hydrated Lime	Whaka Terrace

Table 5.1 List of the Previous work carried out on the chemical stabilisation of Port Hills Loess. Hydrated Lime = $Ca(OH)_2$; Quicklime = CaO; Phosphoric acid = H_3PO_4; Gypsum = $CaSO_4.2H_2O$.

Parameter	Untreated	1 %	2 %	4 %	Notes
Erosion	E 180	NE	NE	NE	Yetton(1986) Pinhole test (see 2.2.1.1)
Dispersion	3-4	1	1	1	Modified crumb test (see Appendix F.1)
Slaking %	12	99.3	-	-	Jar slake test (see 2.2.3.4)
Swelling %	14	2.83	1.9	0.2	Uniaxial swelling strain (see Appendix H.1)
Max Dry Density (t/m-3)	1.86	1.79	1.78	1.72	CaO reduces density
Optimum w%	13	14.2	14.6	15.5	CaO increases OWC
Permeability (m/s)	2 x 10-8	4.5x10-6	5.6x10-6	6.7x10-6	CaO increases permeability
Strength (KPa)	210	525	570	390	Unconfined compressive strength
Cohesion (KPa)	30	47	56	64	Undrained Direct shear box test
			45	43	

Table 5.2 The geotechnical characteristics of remoulded Whaka terrace loess stabilised with 0 (untreated), 1, 2 and 4 % Quicklime. All results are from samples that were moist cured for 14 days at 99 % humidity and 20 °C.

5.2.3 Sample Collection

A 500 kg bulk sample (consisting of twenty 25 kg bags of soil) was taken from soil heaps resulting from previous excavation at the Ahuriri loess quarry. A site inspection carried out before sample collection showed that the loess at the Ahuriri quarry is quite variable in its nature. Figure 5.1 is a face log of the quarry showing the major soil layers. As described in Chapter 3, a number of layers with low clay contents occur in the upper part of the quarry while the bulk of the soil at the quarry has a silt with some clay and fine silt texture.

Tests were carried to determine the geotechnical properties of the soil from a number of locations around the quarry. The results of the tests (Fig. 5.1) show that the low clay content layers have considerably less clay and similar sand contents than the 'silt with some clay and fine sand' loess which makes up most of the loess in the quarry. Crumb test results ranged between 1 and 2, indicating that the loess was either non dispersive or slightly dispersive. All of the samples from the clay poor layers indicated crumb grades of 1. The interpretation was made that the low crumb grade of the clay poor layers was the result of the fact that they had low clay contents and as a result produced small colloidal clouds when immersed in water. The modified British standards pinhole test indicated that erodibility ranged between NE4 (potentially erodible) to E1 (highly erodible). Low cohesion as a result of relatively low clay content is probably the main reason for the high erodibility.

5.2.4 Laboratory Investigations

5.2.4.1 Sample Preparation

a) Untreated Samples

Twenty proctor mould samples were compacted at optimum moisture content (OMC). They were then left to "moist cure"(at 99% relative humidity and 20°C) in the fog room in the University of Canterbury Civil Engineering Department for fourteen days. The average dry density of the compacted samples was 1748 kg/m^3, which is 98.2% of the maximum dry density (see section 5.2.3.4).

Selected geotechnical characteristics									
Sample #	Pinhole Erosion	Crumb test	Dry Density (kg/m3)	Atterberg Limits			Grain size		
				L.L	P.L	P.I	% S	% Z	% C
1	NE4	2	1560	-	-	-	13	74.2	12.8
2	-	1	-	-	-	-	15	76.1	8.9
3	E2	1	1540	-	-	-	-	-	-
4	-	1	-	29	15	14	10.4	64	25.6
5	-	1	-	-	-	-	17.8	78.6	3.6
6	-	2	-	23	17	6	16.4	68.6	15
7	E1	1	1290	-	-	-	17.7	70.6	11.7
8	E2	2	-	-	-	-	-	-	-
9	E2	1	1630	24	17	7	20.3	61.5	18.2
10	-	2	-	23	17	6	19.2	62.3	18.5
11	E1	1	-	-	-	-	-	-	-
12	-	2	1720	-	-	-	16.8	69.7	13.5
13	-	1	-	-	-	-	14.9	82.8	2.3
14	-	2	-	-	-	-	17.2	74.9	7.9
15	-	2	-	-	-	-	21.1	70.5	8.4
16	NE4	2	1660	24	16	8	15.1	66.9	18
17	-	2	-	-	-	-	16.6	73.6	9.8
18	NE4	1	1730	-	-	-	16.5	71.7	11.8
19	E2	2	1540	-	-	-	-	-	-
20	-	1	-	-	-	-	13.2	75	11.8
21	E1	1	1560	-	-	-	-	-	-

LEGEND

Sample locations

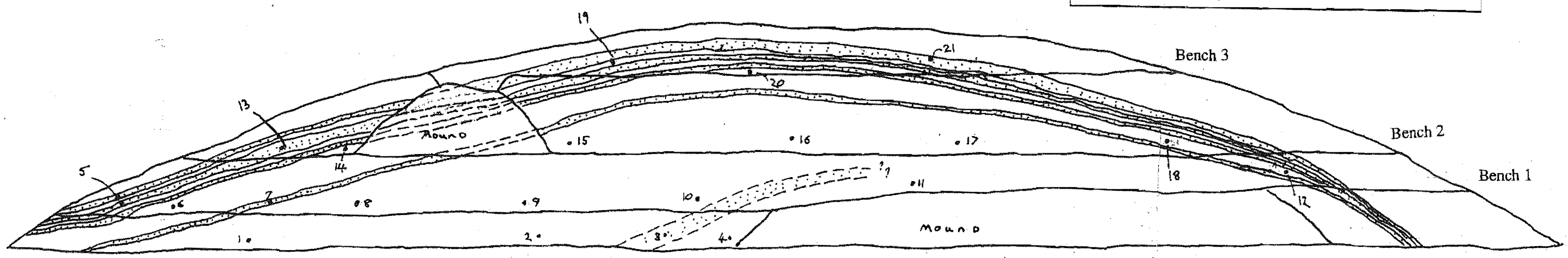
Unweathered, dry, loose, grey silt with some fine sand.

Unweathered, moist, compact, greyish brown silt with some clay and fine sand.

0 10 20

M

Note: Quarry dimensions and sample locations are approximate. Only the major soil layers are shown



AHURIRI QUARRY

Figure 5.1: Face log of the Ahuriri Loess Quarry.

b) Treated Samples

The 'slake' method of adding quicklime to the soil was designed to represent field conditions. The method is shown below:

1. Spread the soil out on a sheet of plastic.
2. Scatter quicklime chips over the soil.
3. Pour the amount of water required to achieve OMC over the chips, ensure that all of the chips dissolve.
4. Mix the soil well so that the activated quicklime is spread throughout the sample. (Note: As the quicklime becomes hydrated, it will give off considerable heat and some of the water will be lost as steam. It is therefore necessary to add about 10% more water than would normally be required to attain OMC).
5. To allow the quicklime to react with the soil, the treated soil was then left to condition for three days.

Ten samples were compacted at OMC and left to moist cure for 14 days. The average dry density of the compacted moulds was 1702 kg/m^3 which is 98.03% of the maximum dry density (see section 5.2.4.3). For pinhole and uniaxial expansion tests on both treated and untreated samples, 35.5mm diameter soil samples were extracted from the moulds (using the equipment described in Appendix A) after the 14 day curing period.

5.2.4.2 Soil Classification Tests

Table 5.3 shows the results of the grain size analyses and atterberg limit tests that were carried out.

a) Grain Size

To reduce error, four tests were carried out on both the treated and untreated samples. The results show that the treated soil has 0.9% less clay and 1% more sand than the untreated soil. The increase in sand content was caused by small chips of un-reacted quicklime in the soil. Tehrani (1988) found that soil stabilised with 2% quicklime had 6% less clay and 18% more sand than the untreated soil. In a study of lime stabilisation of loess from Westmoreland, Glassey (1986) also obtained similar results. It is the authors opinion that the grain size distribution of the treated soil is dependent on the extent of disagregation applied to the soil during grain size analysis. If both the treated and untreated soils are completely disagregated and dispersed according to grain size analysis methodology, then the grain size distribution of the two soils will be very similar. The grain size distribution envelopes for the treated and untreated samples are shown in Appendix D.

b) Atterberg Limits

The results show that 2.5% quicklime decreases plasticity from 4 to 2. This result is considerably different to Glassey (1986) who found that the addition of 2.5% hydrated lime dramatically increased the liquid limit (from 23 to 34) and slightly increased the plastic limit (from 16 to 22) with a resultant increase in the plasticity index from 7 to 13. Tehrani (1988) found that 2% quicklime also increased plasticity (from 7 to 10). Although Tehrani and Glassey carried out work on loess from different sites of the Port Hills, the large differences in plasticity modifications by quicklime is surprising given the fact that the clay mineralogy from all the sites is very similar (i.e dominated by illite). The results obtained in this project are in accordance with most of the international literature which suggests that lime reduces soil plasticity (Ingles and Metcalf, 1973).

5.2.4.3 Physical properties

a) Maximum Dry density (MDD)/Optimum moisture content (OMC)

MDD/OMC testing was carried out by the technicians at the Fulton Hogan Civil Engineering laboratory. The results are shown in Table 5.4. The untreated loess was found to have a maximum dry density of 1780 kg/m^3 and an optimum water content of 15%. The treated loess was found to have a maximum dry density of 1736 kg/m^3 and an optimum water content of 16.4%. Very similar results were determined by Evans (1978): untreated MDD/OMC = 1775 and 14%, 3% lime treated MDD/OMC = 1725 and 17%. Figure 5.2 shows the dry density/water content curves for the two samples.

Previous research (e.g Winterkorn, 1975 and Alexander et. al., 1972) has shown that the effect of quicklime is to decrease MDD and increase OMC. This characteristic is also evident from the work of Glassey (1986), Tehrani (1988) and this project.

	Treated	Untreated
Sand %	14.3	13.3
Silt %	75.4	75.5
Clay %	10.3	11.2
Liquid Limit	24	23
Plastic Limit	22	19
Plasticity Index	2	4

Table 5.3 Results of the soil classification tests carried out on 2.5% quicklime treated and untreated Ahuriri quarry loess.

	Treated	Untreated	Notes
Max dry density Kg/m3	1736	1780	
Optimum moisture %	16.4	15	
Erodibility	NE1	E2	British standards Pinhole test
Dispersion	1	2	British standards Crumb test
Slake Durability Index	95.4	0	Jar Slake test
Slaking Class	5	1	Jar Slake test
Permeability m/s	3.3 x 10-6	1.4 x10-8	
c' (kPa)	28	0	Effective cohesion
Ø'	42	34.5	Effective ang. of int. friction
Uniaxial Expansion %	0.3	13.8	Confined uniaxial Expansion
Linear Shrinkage %	0.88	0.27	

Table 5.4 Average Geotechnical properties of 2.5% quicklime stabilised and untreated Ahuriri quarry loess samples.

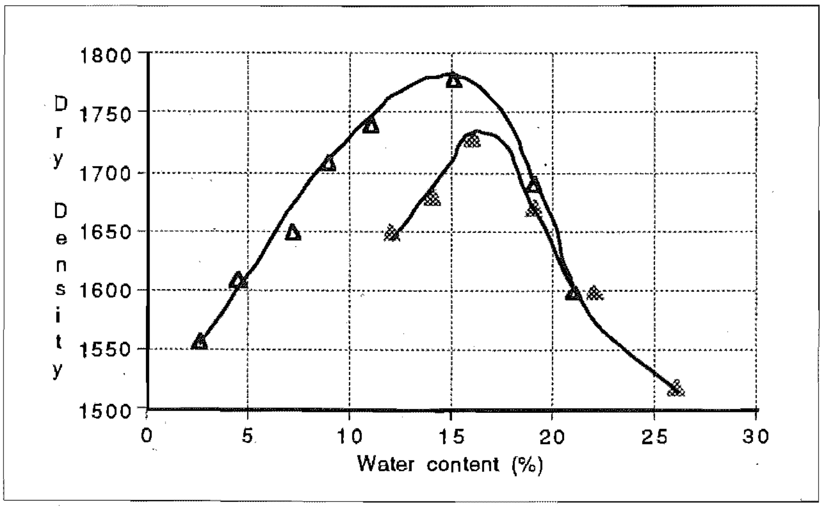


Figure 5.2 The Dry density / water content relationship for untreated (white triangles) and 2.5% quicklime treated (grey triangles) Ahuriri quarry loess.

b) Erodibility

The British standards pinhole test was used to determine susceptibility to erosion. Since tap water was used, dispersion was not a significant factor (see section 4.6.1).Three tests were carried out on both the untreated and the treated samples. The test results (Table 5.4) were consistent, and show that the untreated loess is highly erodible. The addition of 2.5% quicklime makes the soil non-erodible in the pinhole test.

c) Dispersion

The results given in Table 5.4 are the average of five tests carried out on both samples. All five treated samples had a crumb class of 1. The untreated sample was found to have a crumb class range between 1.5 - 2.5 which indicates that the untreated soil is slightly to moderately dispersive. The addition of 2.5% quicklime renders the soil non-dispersive. The reduction in dispersion is in accordance with previous work.

d) Slake Durability

The results given in Table 5.4 are the average of six tests carried out on 2.5% quicklime stabilised samples, and three tests carried out on untreated samples. Quicklime stabilised samples had durabilities in the range of 92.2 to 97.6%. Both the slake durability index and the slaking class results indicate that the untreated soil is prone to extreme slaking. The addition of 2.5% quicklime considerably decreases the damage caused by slaking. Similar results were obtained by Tehrani (1988) and Glassey (1986).

e) Permeability

The results in Table 5.4 show that the addition of 2.5% quicklime increased the permeability from 1.41×10^{-8} to 3.3×10^{-6} m/s. Similar results were obtained by Tehrani (1988). The permeability increase of quicklime stabilised soil results from a lower dry density and a higher porosity . According to Tehrani (1988) the lower dry density results from void space increase resulting from clay mineral flocculation and silt agglomeration.

f) Shear Strength

Drained shear strength tests were carried out on remoulded, consolidated, saturated samples with a shearing rate of 0.0032 mm/minute. At this rate failure occurred after approximately 27 hours. Figures 5.3, 5.4 show the shear stress/normal stress

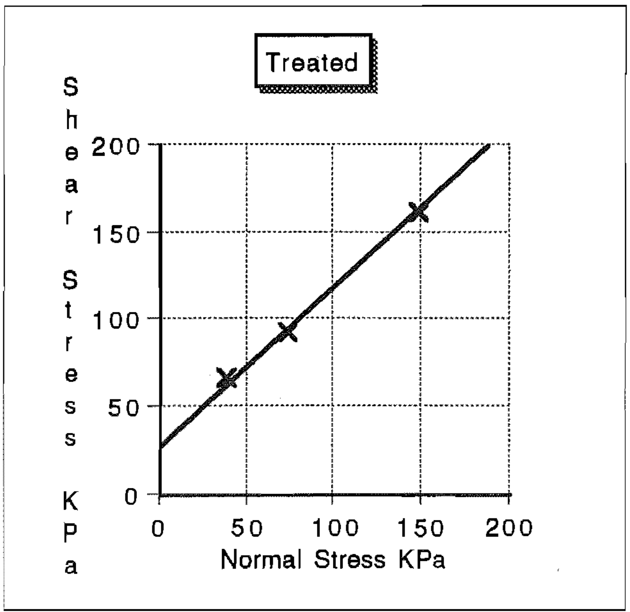


Figure 5.3 Shear stress/normal stress graph for 2.5% quicklime treated samples tested in a drained, consolidated, saturated condition. Rate of shear = 0.0032 mm/min.

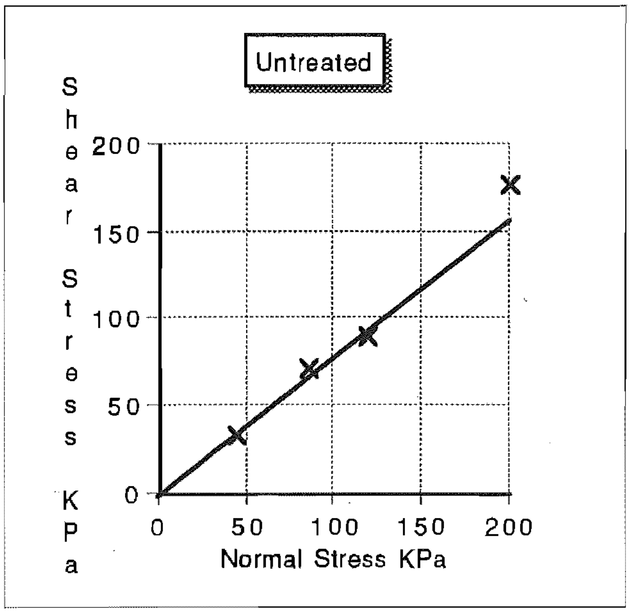


Figure 5.4 Effective Shear stress/normal stress graph for untreated samples tested in a drained, consolidated, saturated condition. Rate of shear = 0.0032 mm/min.

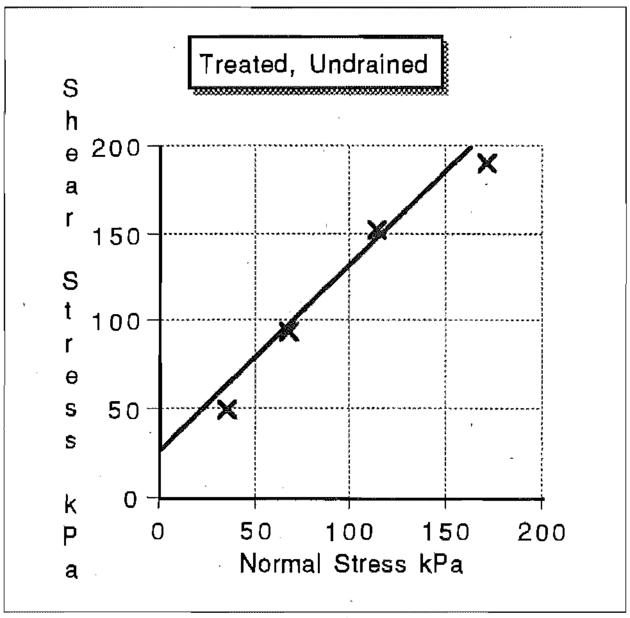


Figure 5.5 Shear stress/normal stress graph for treated samples tested in a undrained, consolidated, saturated condition. Test shear rate = 0.012 mm/min.

graphs which were used to determine the shear strength characteristics shown in Table 5.4. The shear strength/displacement graphs of all the tests that were carried are shown in Appendix J. The shearing rate used in this project was estimated from Chandler and Rodgers (1980) who suggested a rate of between 0.0005 to 0.0009 mm/min for heavy clays. Given that loess (basically a silt) has a considerably higher permeability than clay rich material it was decided that a rate of 0.0032 mm/min would be slow enough for drained testing. Tehrani (1988) carried out unconsolidated, undrained direct shear tests on remoulded, partially saturated samples. A shearing rate of 1.2 mm/min was used. The results (Table 5.2) also indicated an increase in strength with the addition of quicklime.

Undrained tests were also carried out on treated samples. According to Chandler and Rodgers (1980), undrained tests are usually ran at a rate of between 0.01 to 0.03 mm/min, therefore it was decided to use a shearing rate of 0.012 mm/min. The results that were obtained: $\emptyset = 43°$ and $c = 35$ kPa (from Fig 5.5), are very similar to the drained strength test results. However, soil mechanics theory suggests that drained and undrained shear strength characteristics should be considerably different. The similarity between the strength characteristics of the two tests suggests that they may have both been carried out in the drained condition.

g) Uniaxial Expansion and Linear Shrinkage

The results shown in Table 5.4 are the average of two tests. The high uniaxial expansion exhibited by the untreated samples is significantly reduced by the addition of 2.5% quicklime. Yetton (1986) and Tehrani (1988) had similar results. Linear shrinkage was very low for both treated and untreated samples. According to Trangmar (in prep.) the low shrinkage reflects the dominance of weakly weathered illite clay minerals in Port Hills loess.

5.3 Endurazyme Stabilisation

5.3.1 Stabilisation Mechanism

Endurazyme is the trade name given to an Enzyme based chemical stabiliser used in road construction and other related projects. It is manufactured by World Enzymes which are based in Perth, Western Australia. According to the manufacturers, Endurazyme works best with clay soils and gravels with at least 20% finer than 75 microns and a plasticity index greater than 8. When used on a soil with these characteristics, the manufacturers claim the following benefits from using Endurazyme:

1. An improved moisture distribution improves soil workability.
2. On compaction, soil particles are allowed to realign themselves more efficiently. As a result, densities are increased. Typically, density increases of 5% can be achieved for the same compactive effort. After compaction, further enzyme activity allows for a closer and more stable union between soil particles resulting in additional stability.
3. Increased compaction results in strength gains of about 30-50%.
4. Increased compaction and particle realignment reduces permeability.
5. When used in conjunction with other stabilisers such as cement or lime it has the effect of improving the effects of these additives.

Endurazyme comes in a concentrated liquid form which is simply added to water before it is mixed into the soil. World Enzymes recommend an application rate of 1 litre per 3.5 m^3. Endurazyme has been found to be most effective on soils with 20-50% by mass finer than 0.075 mm, a plasticity index greater than 8, and a gravel (2-60mm) content of between 40-75%.

The stabilisation mechanisms of Endurazyme are a closely guarded secret. A brief summary is given below:

"Bioenzyme stabilisers provide a bacterial culture in an enzyme solution. When exposed to the carbon dioxide in the air, the bacteria multiply rapidly and produce large organic molecules, which the enzyme attaches to the clay molecules in the aggregate, blanketing ion exchange points in the clay. This action prevents further absorption of moisture and results in a stable construction material. During the hydration that follows compaction, ionised water forms linkages between the closely packed particles, providing the cementing bond."

From: "Road stabilisation with Bioenzyme Mechanics". World Enzymes Information sheet, 1994.

Examples of the effects of Endurazyme are also given in the Information sheet. A soil with 3% gravel, 34% sand and 63% fines (silt and clay) had its maximum dry density increased by 2.9% (1652 to 1700 kg/m^3) and its optimum moisture content reduced by 7.5% (from 17 to 15.8) when Endurazyme was used to stabilise it. Also, Endurazyme caused a 42% increase of unconfined compressive strength..

5.3.2 Laboratory Programme

Tests were carried out in order to determine the extent to which Endurazyme stabilises Ahuriri quarry loess. It was thought that the low clay content of Ahuriri quarry loess (11.18%) might cause Endurazyme to be ineffective. Therefore, tests were also carried out on loess samples from the Timaru downs with a higher clay percentage of 22.5% to see if the increased clay content improved the extent of Endurazyme stabilisation. For comparative purposes, tests were also carried out on samples stabilised with quicklime and quicklime plus Endurazyme. All samples were moist cured at 99% relative humidity and 20°C for 7 days.

When used for the stabilisation of gravel rich road bases World Enzymes recommend an application rate of 1 litre/3.5m^3. Inquiries were made to World Enzymes as to the how much Endurazyme would be most effective in stabilising loess. As a result of this inquiry it was decided that 1 litre/3.5m^3 of Endurazyme might not have much effect given that loess has less gravel and clay than the soils for which Endurazyme is designed. It was also stated that no benefits would be obtained by using more than 5 litres per 3.5m^3. It was therefore decided to carry out tests at the application rates of 1, 3 and 5 litres per 3.5m^3. Table 5.5 which details the testing programme that was carried out. Most of the emphasis was placed on testing the maximum dry density/optimum moisture content because improved compaction is the most important characteristic of Endurazyme stabilisation. Unconfined compressive strength, Jar slake, pinhole and crumb tests were also carried out.

5.3.3 Maximum Dry Density/Optimum Moisture Content

The results are summarised in Table 5.6. The dry density/water content curves are shown in Figures 5.6-17. The following observations were made about the test results:

1. Endurazyme applied at a rate of 1 litre per 3.5m^3 has little or no effect on the

Sample	MDD/OMC	UCS	Jar Slake	Pinhole
Ahu	Y	Y	Y	Y
Ahu+E	1, 3, 5.	3	3	3
Ahu+Q	1.25, 2.5.	1.25, 2.5	2.5	2.5
Ahu + 1.25%Q/E	1.5, 2.5	1.5, 2.5	-	-
Tim	Y	Y	-	-
Tim+E	1, 3, 5.	3	-	-

Table 5.5 Endurazyme stabilisation laboratory programme showing tests and stabiliser concentration. MDD/OMC = maximum dry density/optimum moisture content; UCS = unconfined compressive strength. Ahu = Ahuriri loess; Tim = Timaru loess; E = Endurazyme, Q = quicklime. The numbers in the boxes refer to stabiliser concentration. 'Y' indicates that tests were carried out on untreated samples. For Endurazyme stabilised samples concentration is in litres / 3.5 m^3. For quicklime stabilised samples the concentration is in % by dry weight.

Soil	Quicklime %	Endurazyme litre/3.5m3	MDD kg/m3	OMC %	MDD Change %
Ahuriri	0	0	1763	14.2	-
Ahuriri	0	1	1766	14.2	0.17
Ahuriri	0	3	1783	14.2	1.13
Ahuriri	0	5	1780	14.7	0.96
Ahuriri	1.25	0	1745	15.8	-1.02
Ahuriri	2.5	0	1713	16.2	-2.8
Ahuriri	1.25	1.5	1738	15.5	-1.42
Ahuriri	1.25	2.5	1748	15.6	-0.85
Timaru	0	0	1790	16.1	-
Timaru	0	1	1788	16.6	-0.11
Timaru	0	3	1810	16	1.12
Timaru	0	5	1800	16.2	0.56

Table 5.6 Max dry density/optimum moisture content test results. MDD change % = the percent increase (positive values) or decrease in maximum dry density as a result of the addition of Endurazyme and/or quicklime.

Quicklime %	Endurazyme litre/3.5m3	Durability %	Erodibility	Crumb Class
0	0	0	E2	2
2.5	0	95.4	NE1	0
0	3	0	E2	2

Table 5.7 The results of durability, erodibility and dispersion tests on untreated, quicklime and endurazyme treated Ahuriri quarry loess.

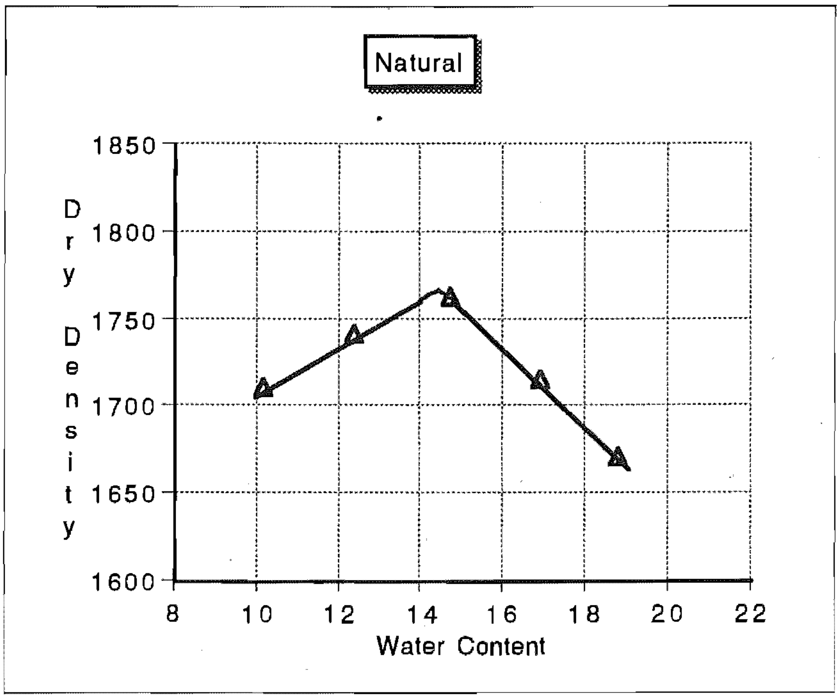


Figure 5.6 Dry Density/Water Content relationship for loess from the Ahuriri Quarry. Dry Density is in Kg/m^3.

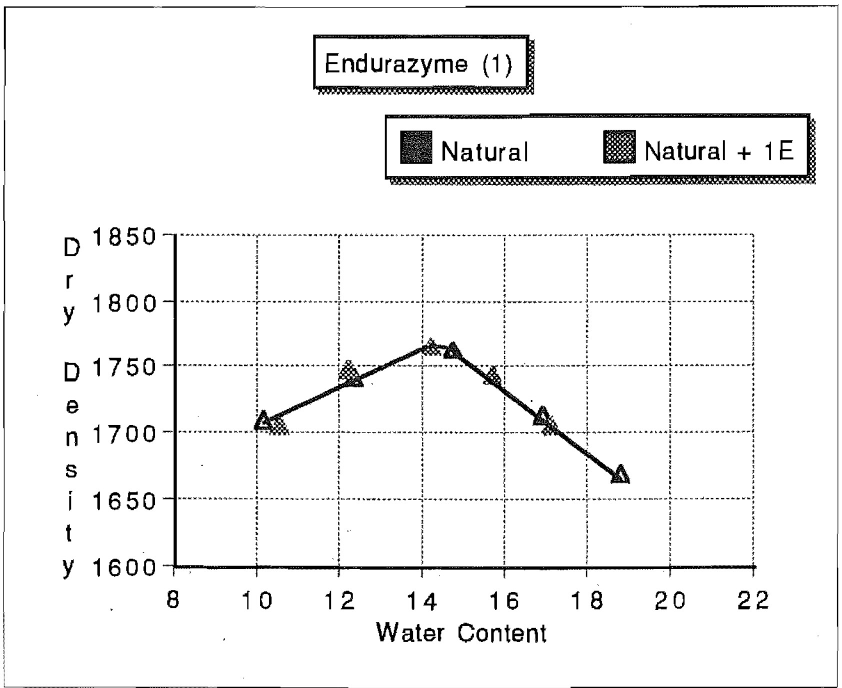


Figure 5.7 Dry Density/Water Content relationship for loess from the Ahuriri Quarry with Endurazyme applied at a rate of 1 litres per 3.5 m^3. Dry Density is in Kg/m^3.

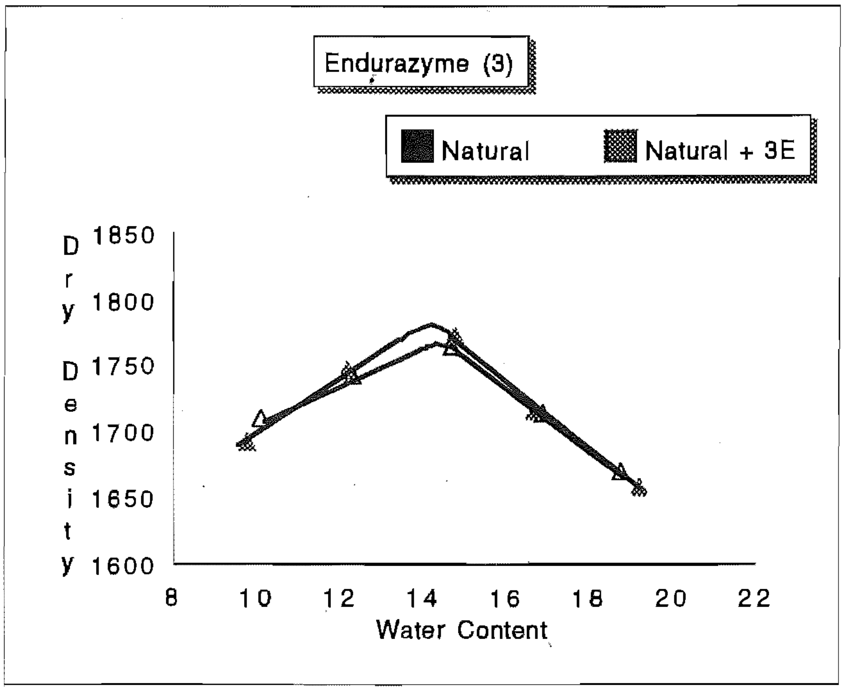


Figure 5.8 Dry Density/Water Content relationship for loess from the Ahuriri quarry with Endurazyme applied at a rate of 3 litres per 3.5 cubic metres. Dry Density is in Kg/m^3.

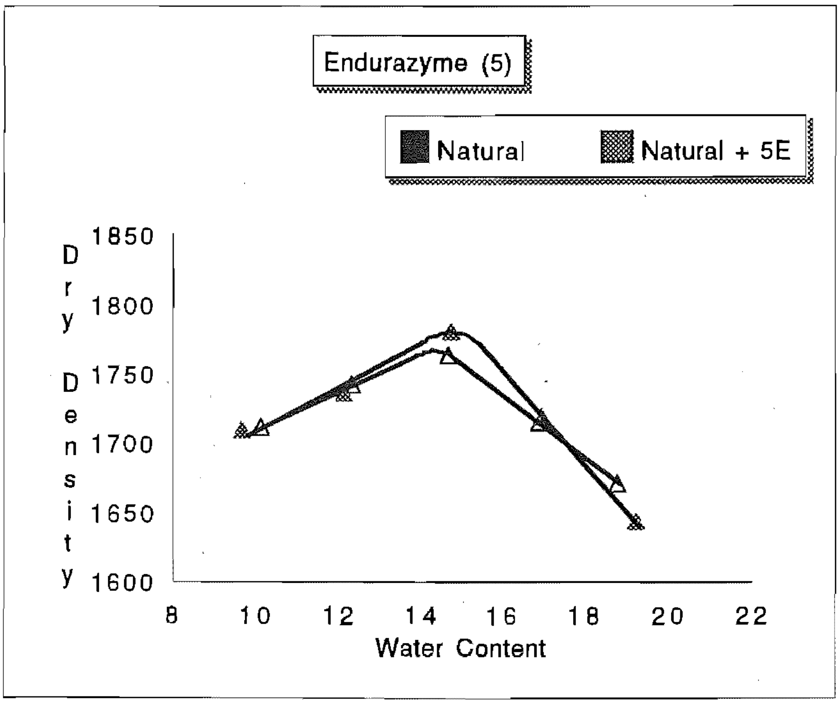


Figure 5.9 Dry Density/Water Content relationship for loess from the Ahuriri Quarry with Endurazyme applied at a rate of 5 litres per 3.5 cubic metres. Dry Density is in Kg/m^3.

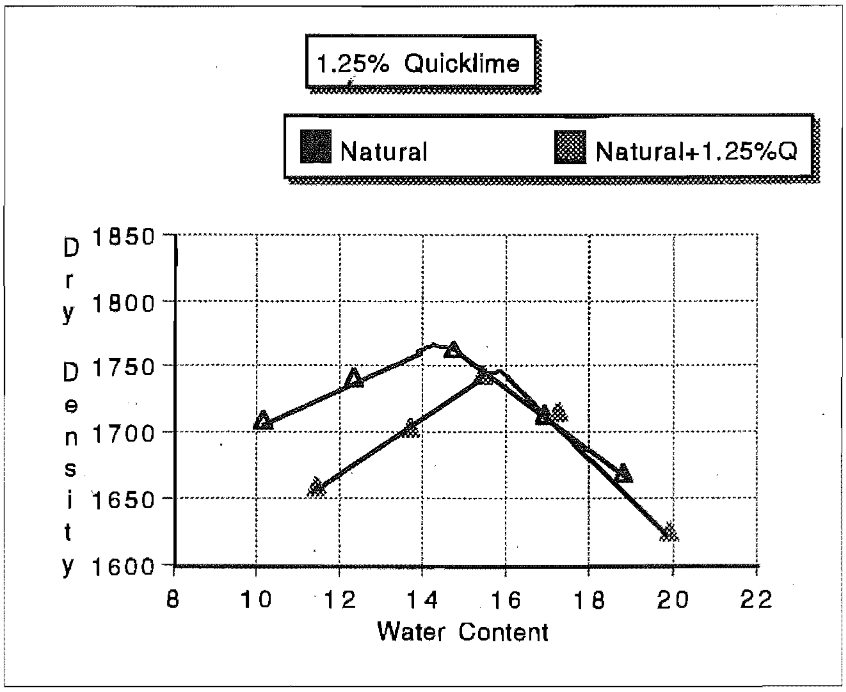


Figure 5.10 Dry Density/Water Content relationship for loess from the Ahuriri Quarry with 1.25% quicklime. Dry Density is in Kg/m^3.

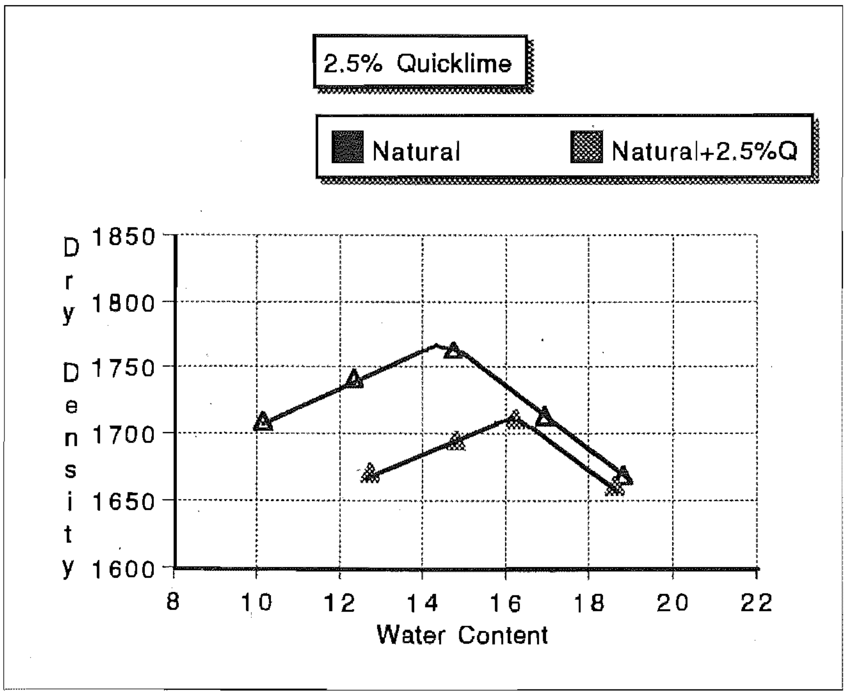


Figure 5.11 Dry Density/Water Content relationship for loess from the Ahuriri Quarry with 2.5% quicklime. Dry Density is in Kg/m^3.

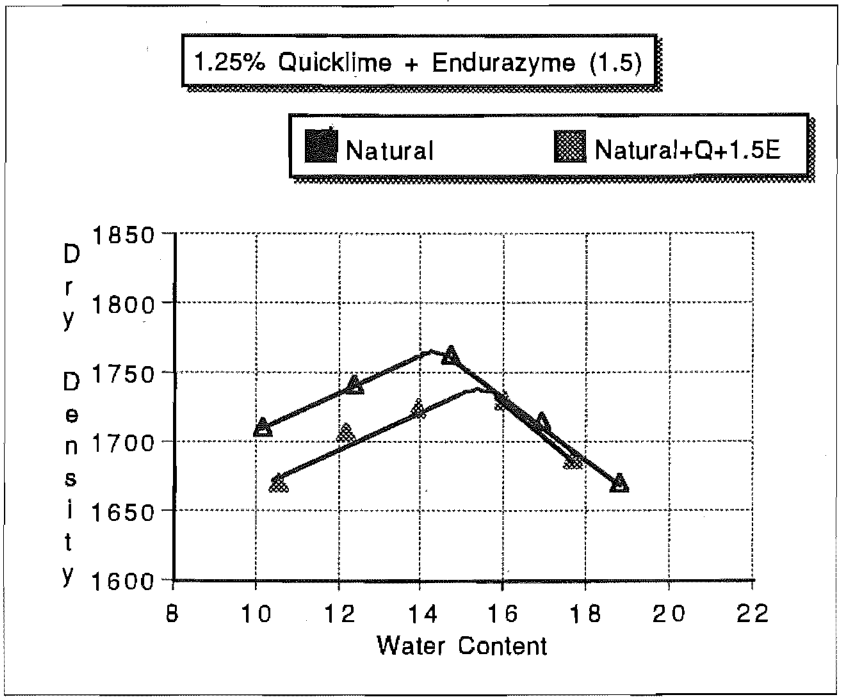


Figure 5.12 Dry Density/Water Content relationship for loess from the Ahuriri Quarry with Endurazyme applied at a rate of 1.5 litres per 3.5 cubic metres and 1.25% quicklime. Dry Density is in Kg/m3.

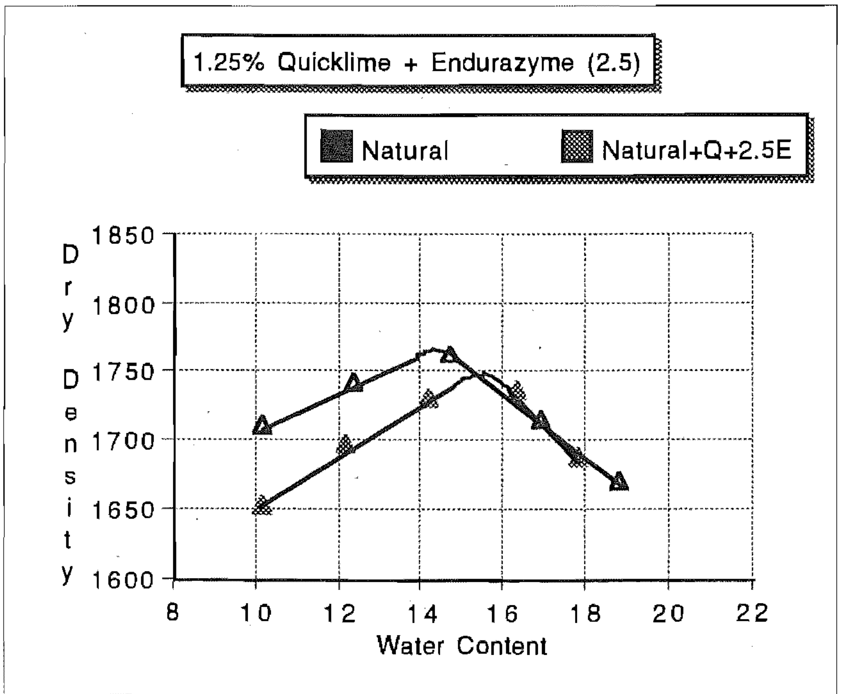


Figure 5.13 Dry Density/Water Content relationship for loess from the Ahuriri Quarry with Endurazyme applied at a rate of 2.5 litres per 3.5 cubic metres and 1.25% quicklime. Dry Density is in Kg/m^3.

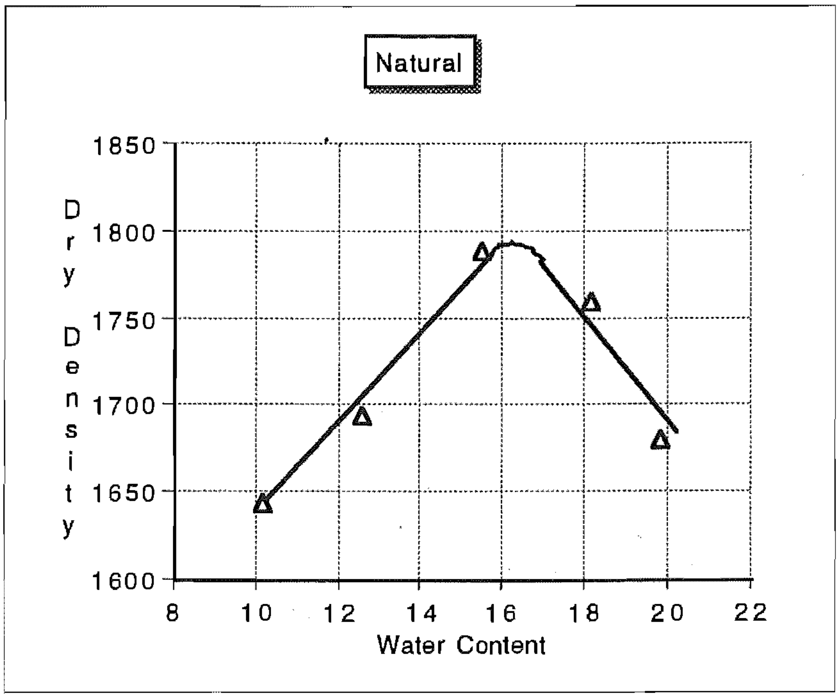


Figure 5.14 Dry Density/Water Content relationship for loess from the Timaru quarry . Dry Density is in Kg/m^3.

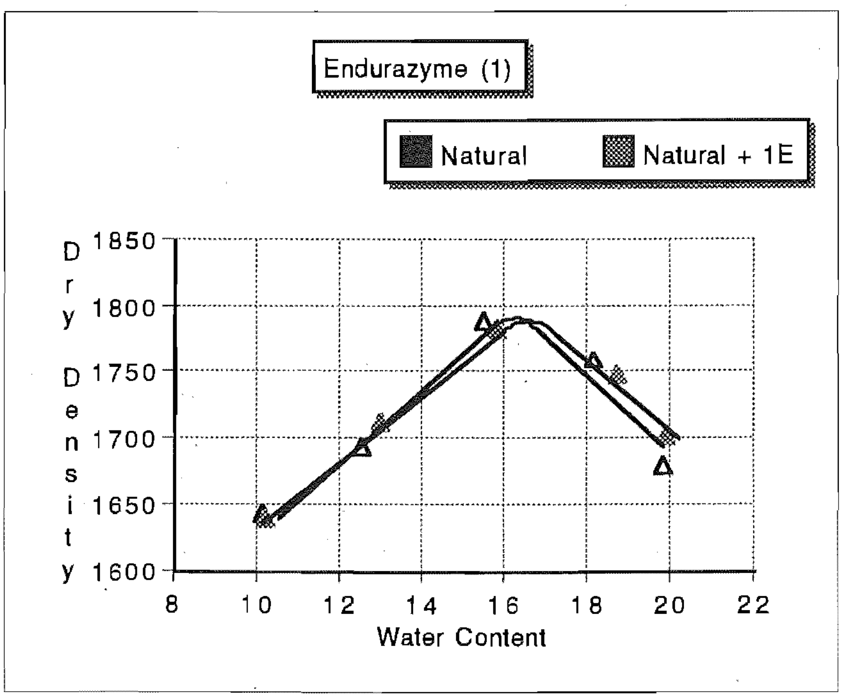


Figure 5.15 Dry Density/Water Content relationship for loess from the Timaru quarry with Endurazyme applied at a rate of 1 litre per 3.5 cubic metres. Dry Density is in Kg/m^3.

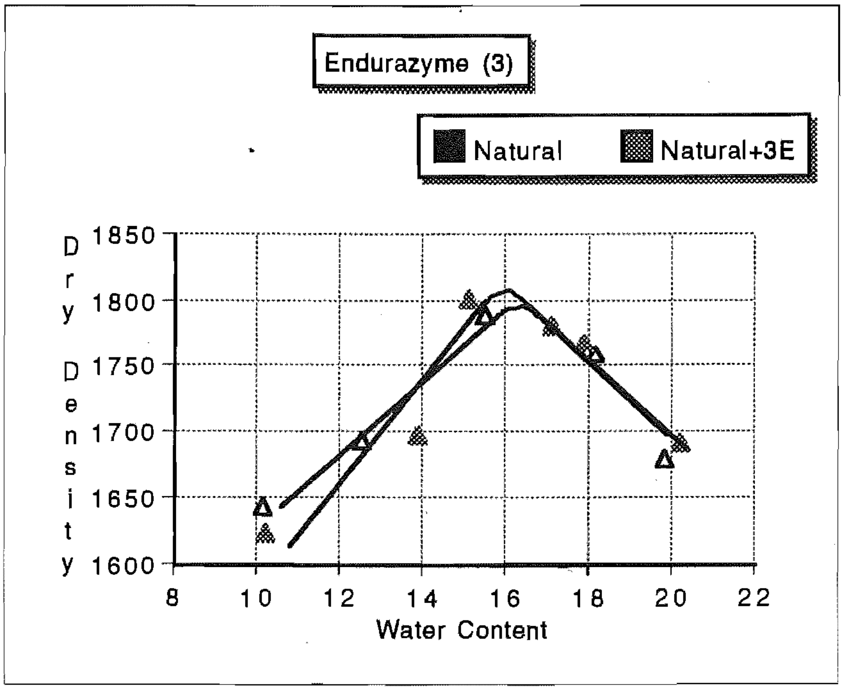


Figure 5.16 Dry Density/Water Content relationship for loess from the Timaru quarry with Endurazyme applied at a rate of 3 litres per 3.5 cubic metres. Dry Density is in Kg/m^3.

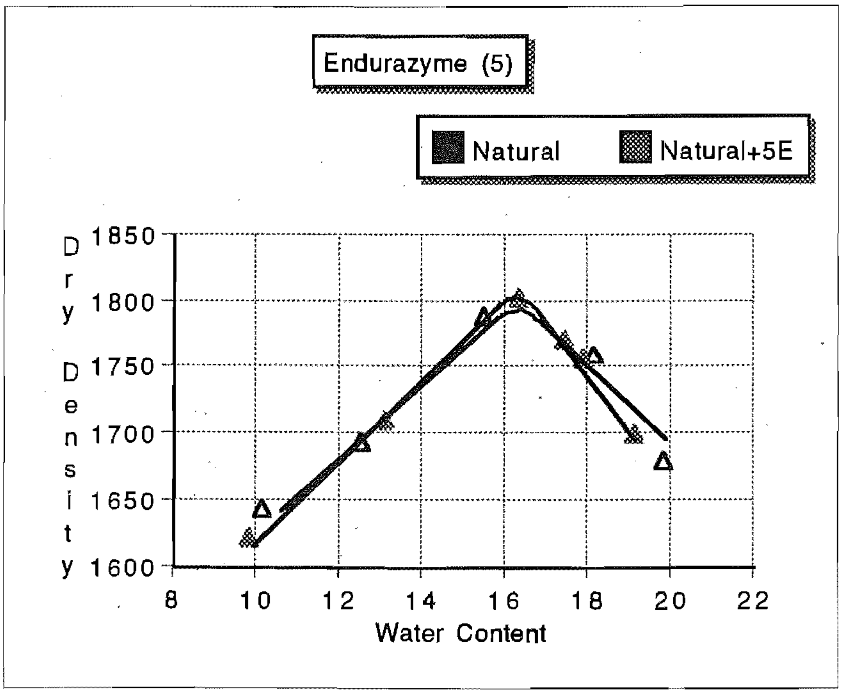


Figure 5.17 Dry Density/Water Content relationship for loess from the Timaru quarry with Endurazyme applied at a rate of 5 litres per 3.5 cubic metres. Dry Density is in Kg/m^3.

compactive characteristics of Ahuriri or Timaru loess.

2. Endurazyme applied at a rate of 3 litres per $3.5m^3$ increases the maximum dry density of Ahuriri and Timaru loess by approximately 1%. The increase of maximum dry density (1%) of the Endurazyme stabilised soil is not statistically significant and does not warrant the use of Endurazyme as a means of increasing density.

3. Increasing the application rate from 3 to 5 litres per $3.5m^3$ does not improve the compaction characteristics of either soils. The dry density of Timaru loess seems to decrease at an application rate of 5 litres/m^3. Given the large scatter in the maximum dry density/OMC graphs for Timaru loess, this decrease could easily be the result of experimental error.

4. Endurazyme applied at rates of 1.5 and 2.5 litres per 3.5 m^3 has no effect on the compaction characteristics of Ahuriri loess with 1.25% quicklime.

5. Timaru loess is stabilised to approximately the same extent as Ahuriri loess. Therefore it seems that the higher clay content of Timaru loess does not appear to improve the affects of Endurazyme.

6. Timaru loess has a significantly higher maximum density than Ahuriri loess. This probably results from grain size distribution differences between the two soils.

5.3.4 Unconfined Compressive Strength

All of the results shown in Table 5.8 represent the average of three tests. The stress/displacement curves for all of the tests are given in Appendix J.

Tests were carried out on samples which were compacted in proctor moulds at optimum moisture comtent. After two weeks moist curing, the samples were left to air dry at room temperature for 7 days. Tests were then carried out on the air dried samples. After drying the samples had water contents of between 2-4%. From the test results, the following observations were made:

1. Endurazyme at a concentration of 3 litres per $3.5m^3$ does not increase the UCS of Ahuriri quarry loess. In fact it was found that Endurazyme stabilisation actually reduced

Soil	Quicklime %	Endurazyme litre/3.5m3	Dry Density kg/m3	Water Content %	UCS MPa	Strain %	E MPa
Ahuriri	0	0	1789	2.4	1.73	3.91	44.38
Ahuriri	0	3	1786	2.7	1.54	3.27	47.52
Ahuriri	1.25	0	1746	2.5	0.68	2.76	26.11
Ahuriri	2.5	0	1688	2.5	0.79	2.8	28.81
Ahuriri	1.25	1.5	1729	2.9	0.61	2.95	20.57
Ahuriri	1.25	2.5	1732	3.9	0.71	3.07	23.08
Timaru	0	0	-	-	1.82	4.03	46.32
Timaru	0	1	-	-	1.71	3.57	48.71

Table 5.8 Unconfined compressive strength (UCS) results. E = Modulas of elasticity.

UCS by about 12%. Tests carried out on Timaru loess indicate that Endurazyme at a concentration of 1 litre per $3.5m^3$ reduces UCS by about 6%.

2. Air dried untreated Ahuriri loess is 2.54 times stronger than 1.25% quicklime stabilised Ahuriri quarry loess and 2.19 times stronger than 2.5% quicklime stabilised Ahuriri loess. This result would appear to be contrary to the results given in section 5.2.4 where it was found that quicklime stabilised samples were stronger than untreated samples.

Glassey (1986) also found that air dried (water content of about 3%) loess attains considerably higher strength values than air dried 2.5% lime stabilised loess. It was also found that strength values for both treated and untreated air dried samples were considerably higher than for soils in the moist condition (water content of about 15%). This effect was attributed to soil suction. The addition of lime or quicklime seems to reduce the suction effect and the air dried quicklime samples are as a result weaker than the untreated samples. When the soil is moist, the suction effect is reduced and lime plays a more important role in the strength characteristics. Glassey found that in the moist condition, quicklime increased strength.

5.3.5 Slake Durability

The test results are summarised in Table 5.7. The Ahuriri 2.5% quicklime and untreated results are from previous testing carried out in 5.2.4. The results given for the Endurazyme stabilised sample are based on just one test. It appears from the results that Endurazyme has no observable effect on the slaking characteristics of Ahuriri quarry loess.

5.3.6 Erosive and dispersive properties

The crumb test was used to determine dispersion and the modified British standards pinhole test (Appendix G) was used to determine erodibility.The test results are summarised in Table 5.7. The Ahuriri 2.5% quicklime and untreated results are from previous testing carried out in 5.2.4 and all results are the average of three tests. The results indicate that Endurazyme does not decrease soil erodibility or reduce dispersivity.

5.4 Synthesis

1.The addition of 2.5 % quicklime had the following affects on the properties of loess from the Ahuriri quarry:

- Reduced plasticity from 4 to 2.
-Decreased maximum dry density from 1780 kg/m^3 to 1736 kg/m^3, and increased optimum moisture content from 15 to 16.4 %.
- Made the soil non dispersive and non erodible.
- Increased permeability from 1.41 x 10^{-8} to 3.3 x 10^{-6} m/s.
- Increased drained cohesion from 0 to 28 kPa, and also increased the angle of internal friction from 34.5 to 42 degrees.
- Reduced Uniaxial expansion from 13.18 to 0.3%.

2. Endurazyme applied at a rate of 1 litre/3.5m^3 has a negligible effect on the maximum dry densities of both Ahuriri and Timaru loess. Endurazyme applied at a rate of 3 litres/3.5m^3 increases maximum dry density by of Timaru and Ahuriri loess by about 1%. Increasing the application rate from 3 to 5 litres/m^3 does not appear to have any effect on the maximum dry density of either Timaru or Ahuriri loess.

3. Endurazyme applied at a rate of 3 litres/3.5m^3 has negligible effect on the unconfined compressive strength of both Ahuriri and Timaru loess.

4. Endurazyme does not seem to have any affect on the properties of quicklime stabilised loess.

In summary it seems that Endurazyme has essentially no affect on the properties of Ahuriri quarry loess. As the Endurazyme stabilisation process involves an interaction between clay minerals and enzymes it is likely that the relatively low activity of the clay minerals in Port Hills loess is a major reason for the low reactivity of Endurazyme. The manufacturers recommend a gravel content of between 40 to 75%. Given that the loess tested in this project is free of gravel, it seems likely that this has an affect on the lack of reaction of endurazyme in loess.

Chapter 6: Summary and Conclusions

1. A number of different tests have been used to determine the susceptibility of soils to sub-surface erosion. Due to the complex nature of the sub-surface erosion process and the large variability in soil characteristics no one single test can be relied upon to predict field erodibility with absolute certainty. In light of this fact, it is desirable to design a testing programme in which all of the properties which are likely to have an affect on the extent of sub-surface erosion are investigated.

2. The pinhole test is not a reliable test of dispersion for soils in which factors other than dispersion play even a small role in determining the erodibility of a soil. When used as an erodibility test, the pinhole test is useful in that it simulates practical erosion conditions in which the processes of slaking and clay mineral dispersion both influence the extent of erodibility.

3. Most of the loess deposits found on the South Canterbury Downlands, including the Timaru Downs, are free of tunnel gully erosion. However, tunnel gully erosion was identified in two parts of South Canterbury: the upper Pareora River and the hillsides on the western fringe of the Timaru Downs where the Taiko site is located.

4. Extensive subsurface erosion was observed in Timaru loess that has been used as fill material. This shows that in its remoulded form, Timaru loess is potentially erodible even though it is free of tunnel gully erosion in its natural state. Therefore, precautions should be taken to prevent erosion when Timaru loess is used as a fill material. Methods such as drainage and chemical stabilisation have been found to be effective in reducing the erosion of Port Hills loess.

5. Quartz and feldspar , which are non clay minerals, make up a considerable part (25 -

52%) of the clay sized mineral fraction of all samples. It is considered that this is a major reason for the low activity of South Island loess. As well, the low clay mineral content would reduce cohesion and as a result make the soils more prone to erosion. The high non clay mineral content (52%) in the clay sized fraction of Wither Hills loess may be one of the causes of the extreme tunnel gully erosion that occurs on the Wither Hills.

6. In general, laboratory test results did not correlate fully with field erodibility. The two non tunnel gullied soils exhibited some characteristics which suggested that they should be prone to tunnel gully erosion. For instance, the Barrys Bay soil had very high uniaxial expansion and was also dispersive. The Timaru soil was dispersive, and was also erodible as indicated by the pinhole test. The lack of correlation between laboratory test data and field erodibility suggests that other factors play important parts in determining if a soil is prone to tunnel gully erosion. One of these factors is likely to be the extent of gammation as a result of soil weathering. The two tunnel gully erosion free sites: Timaru and Barrys Bay have soil profiles in which gammation veining is a prominent feature. The Port Hills, Wither Hills and Taiko sites which are prone to tunnel gully erosion have non-gammate soil profiles. Evidence from Laffan (1977b) suggests that the gammate material is non dispersive and has a major influence on the non tunnel gully erodibility of Timaru loess.

Another important controlling factor in the occurrence of tunnel gully erosion is the extent of devegetation. Given that Wither Hills loess has approximately the same potential erodibility as Port Hills loess, the considerably higher magnitude of tunnel gully erosion on the Wither Hills indicates that the extreme over-grazing and rabbit infestation which occurred on the Wither Hills has had a major influence on the extent of tunnel gully erosion.

In summary, all of the loess deposits studied have properties which indicate that they are potentially susceptible to tunnel gully erosion. It seems that other factors like climate, land use and soil profile characteristics are important factors in determining the occurrence of sub-surface erosion.

7. Endurazyme has a negligible effect on both the maximum dry density and unconfined compressive strength of both Ahuriri and Timaru loess.

References

Alley, P.J. (1966) Cashmere Hills Loess. N.Z Engineering, vol. 11, no. 10. p 424.

Alexander, M.L.; Smith, R.E. and Sherman, G.B. (1972) *Relative Stabilising effect of Various Limes on Clayey Soils*. Highway Research Record, no. 381. pp 27-33.

Arulanandan, K ; Loganathan, P ; and Krone, M. (1975) *Pore and Eroding Fluid Influences on Surface Erosion of Soil* . ASCE, J. Geotech. Engn, vol. 101, no. 1. pp 51-66.

Atkinson, J.H.; Charles, J.A. and Mhach, H.K. (1990) *Examination of erosion resistance of clays in embankment dams*. Quart. J. Eng. Geol, vol 23. pp 103-108.

Barratt, B.C. (1981) *Micromorphology of a yellow-grey earth to yellow-brown earth soil sequence on loess in Canterbury, Otago and Southland, New Zealand*. N.Z soil Bureau Scientific report, #45. 44 p.

Bates, B.D. (1979) *Natural piping in Loess: An Example of Subsrface Water Movement, Port Hills N.Z.*. Msc Thesis, (Geography) University of Canterbury.

Bathurst, E.T.J. (1989) *Water Supplies of Christchurch District*. Chemistry Division, DSIR. Report no. CD 2407.

Bell, D.H. (1981) *Dispersive Loessial Soils of the Port Hills, Christchurch*. Paper presented at conf. on geomechanics and urban planning, Palmerston North.

Bell, D.H.; Glassey P.J. and Yetton, M.D. (1986) *Chemical stabilisation of dispersive loessial soils, Banks Peninsula, Canterbury, New Zealand*. 5th International IAEG congress, Buenos Aires. pp 2193-2207.

Bell, D.H. and Pettinga, J.R. (1984) Presentation of Geological Data. I.P.E.N.Z. Proc. Tech. Group, vol. 9 issue 4G pp 14.1-14.35.

Bell, D.H. and Trangmar, B.B. (1987) *Regolith Materials and Erosion Processes on the Port Hills, Christchurch, New Zealand*. 5th International Conference and field workshop on landslides, Part 2. pp 93-105.

Bell, F.G. (1983) *Engineering properties of Soils and Rocks*. Butterworths. 149 p.

Bell, F.G. and Maud, R.R. (1994a) *Dispersive soils: a review from a South African Perspective*. Quart. J. Eng. Geol. vol. 27. pp 195-210.

Bell, F.G. and Maud, R.R. (1994b) *Dispersive Soils and Earth Dams with some Experiences from South Africa*. Bull. Ass.Eng. Geol. vol. 31, no. 4. pp. 433 - 446.

Birrell, K.S.; and Packard, R.Q. (1953) *Some physical properties of New Zealand "loess"*. N.Z J. Sci. Tech, vol b35. pp 30-35.

Brindley, G.W. and Brown, G. (1980) *Crystal structures of clay minerals and their X-ray identification*. Mineralogical society monograph, no. 5. 495 p.

Bruce, J.G. (1972) *Loess Soils in the South Island*. Loess Soils and Problems of Land use on the Downlands of the South Island New Zealand. Otago catchment board publ. No. 4, pp 1-

Bruce, J.G.; Ives, D.W. and Leamy, M.L. (1973) *Maps and Sections Showing the Distribution and Stratigraphy of South Island Loess Deposits, New Zealand.* 1: 1 000 000. N.Z. Soil Survey Report 7.

Chandler and Rodgers. (1980) *Triaxial and Direct Shear Testing*. University of Waikato, department of Earth Sciences. Geomechanics manual no. 1.

Cole, B.A. ; Rainmansen, C.; Maiklad, P.; Liggins, T.B.; and Chirapuntu, S. (1977) Dispersive Clay in Irrigation Dams in Thailand. *Dispersive Clays, Related Piping, and Erosion in Geotechnical Projects*. J.L Sherard and R.S Decker, Eds., American Society for testing and materials. pp 13-25.

Coumoulos, D.G. (1977) *Experience with Studies of Clay erodibility in Greece*. Dispersive Clays, Related Piping, and Erosion in Geotechnical Projects, J.L Sherard and R.S Decker, Eds., American Society for testing and materials. pp 42-57.

Craft, C.D. & Acciardi, R.G. (1984) *Failure of Pore-Water Analyses for Dispersion*. Journal of Geotechnical Engineering, vol. 110, No. 4. pp 459-472.

Craig, R.F. (1992) *Soil Mechanics*. Chapman and Hall. 427 p.

Cramptom, N.A. (1985) *Engineering Geological Aspects of the Lttelton-Woolston LPG pipeline.* Msc Thesis, (Eng. Geology) University of Canterbury.

Crouch, R.J.; McGarity, J.W. and Storrier, R.R. (1986) *Tunnel Formation Processes in the Riverina Area of N.S.W Australia*. Earth Surface Processes and Landforms, vol. 11. pp: 157-168.

Decker, R.S. and Dunnigan, L.P. (1977) *Development and Use of the Soil Conservation Service Dispersion Test.* Dispersive Clays, Related Piping, and Erosion in Geotechnical Projects, J.L Sherard and R.S Decker, Eds., American Society for testing and materials. pp 94-110.

Diamond, S. and Kinter, E.B. (1965) *Mechanisms of Soil-Lime Stabilisation, an Interperative Review*. Highway Research Record 92. pp 38-58.

Donaldson, G.W. (1975) *The Occurrence of Dispersive Soil Piping in Central South Africa.* Sixth Regional Conference on Soil Mechanics and Foundation Engineering, Durban, S.A. pp 229-235

Elges, H.F.W.K. (1985) *Dispersive soils*. The Civil Engineer, vol. 27. pp. 347-353.

Emerson, W.W. (1967) *A classification of soil aggregates based on their coherance in water.* Aust. J. of Soil Res, vol S47.

Eslinger, E. and Pevear, D. (1988) *Clay minerals for petroleum Geologists and Engineers.* SEPM short course no 22.

Evans, G.L. (1977) *Erosion tests on loess silt, Banks Peninsula, N.Z.* Proc. 9th ICSMFE Tokyo, vol 2. pp 63-69.

Evans, G.L. (1978) *Stabilising effect of chemical additives in Port Hills Loess.* NWASCO

Res. Conf. Report. 28 p.

Evans, G.L. and Bell, D.H. (1981) *Chemical stabilisation of loess, New Zealand.* Proc. 10th Conf. Soil Mech. and Found. Eng. Stockholm. pp 649-658.

Flanagan, C.P. and Holmgren, G.G.S. (1977) *Factors Affecting Spontaneous Dispersion of soil materials as evidenced by the crumb test.* Dispersive Clays, Related Piping, and Erosion in Geotechnical Projects, J.L Sherard and R.S Decker, Eds., American Society for testing and materials. pp 121-135.

Folk, R.L.; Aandrews, P.B.; and Lewis, D.W. (1970) *Detrital Sedimentary Rock Classification and Nomenclature for use in New Zealand.* N.Z. J. Geol. and Geophys. vol. 13. pp 937-968.

Forsythe, P. (1977) *Experiences in Identification and Treatment, of Dispersive Clays in Mississippi Dams.* Dispersive Clays, Related Piping, and Erosion in Geotechnical Projects, J.L Sherard and R.S Decker, Eds., American Society for testing and materials. pp 135-155.

Gerber, A. and Harmse, H.J. (1987) *Proposed Procedure for Identification of Dispersive soils by Chemical testing.* The Civil Engineer in South Africa, vol. 29. pp: 397-399.

Gibbs, H.S, (1945) Tunnel-gully erosion on the Wither Hills, Malborough. N.Z. J. Sci. Tech. (ser. A), vol 27. pp: 135-146.

Gillot, J.E. (1968) *Clay in Engineering Geology.* Elsevier. 296 p.

Glassey, P.J. (1986) *Geotechnical Properties of Lime Stabalised Loess.* Msc Thesis, (Eng. Geology) University of Canterbury.

Goh, K.M.; Molloy, B.P.J.; Rafter, T.A. (1977) *Radiocarbob Dating of Quaternary Loess Deposits, Banks Peninsula, Canterbury, New Zealand.* Quarternary Research 7. pp 177-196.

Goh, K.M.; Tonkin, P.J.; Rafter, T.A. (1978) *Implications of improved radiocarbon dates of Timaru peats on Quarternary loess stratigraphy.* N.Z J. of Geol. and Geophys, Vol 21, No. 4. pp 463-6.

Goldwater, S. (1990) *Slope Failure in Loess. A detailed Investigation Allendale, Banks Peninsula.* Msc Thesis, (Eng Geol) University of Canterbury.

Goodall, J. (1886) *On the Formation of the Timaru Downs.* Trans. N.Z. Inst. vol 19. pp 455-458.

Gray, D.H. (1989) *Erosion Rate of Disperssive and Non Dispersive Clays.* Discussion. J. of Geotech. Eng. vol 115, no. 12. pp 1823-1824.

Griffiths, E. (1973) *Loess of Banks Peninsula.* N.Z. J. Geol. and Geophys, vol 16, no.3. pp 657- 674.

Griffiths, E. (1974) *Soils of part of the Port Hills and adjacent plains.* N.Z Soil Bur. Bulln. 35.

Grim, R.E. (1968) *Clay mineralogy.* McGraw-Hill Book Company. 596 pp.

Haast, J. von. (1865) *Report on the Geological formation of the Timaru District, in Reference to obtaining a water supply.* Press Office, Christchurch.

Hardcastle, J. (1889) Origin of the Loess Deposit of the Timaru Plateau. Trans. N.Z Inst. vol 22. pp 407-414.

Hardcastle, J. (1908) *Notes on the Geology of South Canterbury.* Herald office, Timaru.

Harrison, S.P.A. and Hill, J.K. (1980) *The Water-Jet Penetration Test-A field test of loess Erodibility.* Third Aus.-N.Z conferance on Geomech, vol. 1. pp 163-164.

Heinzen, R.T. and Arulanandan, K. (1977) *Factors Influencing Dispersive clays and Methods of Identification.* Dispersive clays, Related Piping, and Erosion in Geotechnical projects, J.L Sherard and R.S Decker, Eds., American Society for Testing and Materials. pp 202-207.

Holmgren, G.G.S. and Flanangan, C.P. (1977) *Factors Affecting Spontaneous Dispersion of Soil Materials as Evidenced by the Crumb Test.* Dispersive clays, Related Piping, and Erosion in Geotechnical projects, J.L Sherard and R.S Decker, Eds., American Society for Testing and Materials. pp 218-239.

Hosking, P.L. (1962) *Loess and its Erosion, on the Port Hills, Banks Peninsula.* Msc. Thesis (Geography) University of Canterbury.

Hughes, P.J. (1970) *Tunnel erosion in the Loess of Banks Peninsula.* Msc. Thesis (Geography) University of Canterbury.

Hughes, P.J. (1972) *Slope apect and tunnel erosion in the loess of Banks Peninsula, New Zealand.* J. of Hydrol (N.Z), vol 11. no.2. pp 94-98.

Hutton, F.W. (1882) *Note on the Silt deposits at Lyttelton.* Trans. N.Z. Inst. vol. 15. pp 411-414.

Hutton, F.W. (1905) *The Formation of the Canterbury plains.* Trans. N.Z. Inst. vol. 37. pp 465-472.

Ingles, O.G; and Metcalf, J.B. (1973) *Soil stabilisation, Principles and Practice.* John Wiley and Sons. 374 p.

International Society for Rock Mechanics (1981) Rock Characterisation Testing and Monitoring: ISRM suggested methods. Ed. Brown, E.T. Pergammon Press, Oxford. 211 p.

Ives, D. (1973) *Nature and Distribution of Loess in Canterbury.* N.Z. J. Geol. and Geophys, vol 16, no.3. pp 587-.

Kear, B.S; Gibbs, H.S and Miller, R.B. (1967) *Soils of the Downs and Plains Canterbury and North Otago New Zealand.* N.Z Soil Bur. Bull. 14.

Laffan, M.D. (1973) *Landscape, soils and erosion of a catchment in the Wither Hills, Blenheim.* Christchurch, Lincoln. Unpublished M. Ag. Sc. thesis, University of Canterbury.

Laffan, M.D and Cutler, E.J.B. (1977a) *Landscapes, soils, and erosion of a small catchment in the Wither Hills, Malborough.* Part 1: *Landscape periodicity, slope deposits, and soil* *pattern*. N.Z J. of Sci. vol 20. pp: 37-48.

Laffan, M.D. ; and Cutler, E.J.B. (1977b) *Landscapes, soils, and erosion of a catchment in the Wither Hills, Malborough*. Part 2: *Mechanism of tunnel gully erosion in Wither hill soils from loessial drift and comparison with other loessial soils in the South Island.* N.Z. J. of Sci. vol 20. pp 279-289.

Laffan, M.D; and Sutherland, R.D. (1988) *Treatment of Tunnel-Gully Erosion in Loess Colluvium on the Wither Hills, New Zealand.* Loess, it's Distribution, Geology, and Soils. D.S.I.R. , N.Z. , Soil Bur. , Lower Hutt, New Zealand. pp 81-90.

Lewis, D.W. (1984) *Practical Sedimentology*. Hutchinson Ross Publ. 229 p.

Loveday, J. and Pyle, J. (1973) *The Emerson dispersion test and it's relationship to Hydraulic conductivity.* CSIRO Aust. Divn. Soils Tech. Paper no 15. pp 1-7.

Lynn, I.H. and Eyles. G.O. (1984) *Distribution and severity of tunnel gully erosion in New Zealand.* N.Z. J. of Science, vol. 27. pp 175-186.

Mackwell, J.A. (1986) *Engineering Geological Investigations Wainui-French Farm Area Akaroa County Banks Peninsula.* Msc Thesis, (Eng. Geology) University of Canterbury.

McElroy, C.H. (1987) *The use of Chemical additives to control the erosive behaviour of Dispersed Clays.* Engineering aspects of soil erosion, dispersive clays and loess. Geotechnical-Special publication 10. pp 1-16.

Mclaren, R.G. and Cameron, K.C. (1993) *Soil Science.* Oxford University Press. 294 p.

Miller, D.E.K. (1971) *Soil properties affecting tunnel gully erosion.* Unpublished M. Agr. thesis, Lincoln University.

Molloy, L. (1988) *Soils in the New Zealand Landscape.* Mallison Rendel Publishers, Wellington. 238 p.

Moore, P.J.; Wrigley, R.J.; and Styles, J.R. (1985) *Identification and Amelioration of some Dispersive Soils.* Civil Engng. Trans. (Institute of Engineers Aust.). pp 371-381.

Paaswell, R.E (1970) *Causes and mechanisms of cohesive soil erosion: state of the art*.

Pierson, T.C (1983) *Soil Pipes and Slope Stability.* Quart. J. of Eng. Geol. vol. 16. pp. 1-11.

Pye, K. (1984) *Loess.* Progress in Physical Geography, vol 8, no. 2. pp 176-217.

Rae, S.N; and Tozer, C.G. (Eds.) (1990) *Water and Soil Resources of the Wairau. Nelson-Malborough Regional Council.* Volume 3: *Land and Soil Resources.* 206 p.

Raeside, J.D. (1964) *Loess deposits of the South Island, New Zealand, and soils formed on them.* N.Z. J. of Geol. and Geophys. vol. 7. pp 811-838.

Resendiz, D. (1977) *Relevance of Atterberg limits in Evaluating Piping and Breaching Potential.* Dispersive clays, Related Piping, and Erosion in Geotechnical projects, J.L Sherard and R.S Decker, Eds., American Society for Testing and Materials. pp 341-353.

Ritchie, J.A. (1963) *Earthwork tunnelling and the application of soil testing procedure.* J. Soil

Cons service. N.S.W. Vol 19. pp. 111-129.

Ryker, N.L. (1977) *Encountering Dispersive Clays on Soil Conservation Service Projects in Oklahoma.* Dispersive clays, Related Piping, and Erosion in Geotechnical projects, J.L Sherard and R.S Decker, Eds., American Society for Testing and Materials. p 370-3890.

Schafer, G.J.; and Trangmar, B.B. (1981) *Some Factors Affecting Tunnel Gully erosion.* Proc. 10th Conf. Soil Mech. and Found. Eng. Stockholm. vol 1. pp 481-486.

Shaikh, A.; Ruff, J.F.; Abt, S.R. (1987) *Surface erosion of Compacted pure Clays.* Engineering aspects of soil erosion, dispersive clays and loess. Geotechnical-Special publication 10. pp 67-77.

Shaikh, A.; Ruff, J.F.; Charlie, W.A.; Abt, S.R. (1988) *Erosion Rate of Dispersive and Non-Dispersive Clays.* J. Geotech. Engn. (ASCE), vol. 114, No. 5. pp 589-600.

Sheppard, J.S. and Lambrechtsen, N.C. (1983) *Plant materials and Management Options for Soil Canservation on the Port Hills, Christchurch.* Water and Soil Miscellaneous Publication no. 62. 26 p.

Sherard, J.L.; Decker, R.S. and Ryker, N.L. (1972) *Piping in Earth Dams of Dispersive Clay.* Proc. Specialty Conference on Performance of Earth and Earth Supported structures. pp 589-626.

Sherard, J.L.; Dunnigan, L.P.; Decker, R.S. and Steele, E.F. (1976a) *Pinhole test for identifying dispersive soils.* Geotech. Engng. Divn. ASCE, vol 102, no GT4.

Sherard, J.L.; Dunnigan, L.P. and Decker, R.S. (1976b) *Identification and Nature of Dispersive soils.* J. Geotech. Engn. Divn. ASCE. vol. 102 no. GT4. pp 287-301.

Skempton, A.W. (1953) The Colloidal Activity of Clay. Proceedings of the Seventh International Conferance on Soil Mechanics and Foundation Engineering, vol. 1. pp 57-61.

Sridharan, A.; Sudhakar, M.R. and Dwarkanath, H.N. (1992) *Dispersive Behavior of Nonswelling Clays.* Geotec. Testing Journal. vol. 15, no. 4. pp 380-387.

Tadanier, R. andIngles, O.G. (1985) *Soil Security Test for Water Retaining Structures.* J. Geotech. Engn. (ASCE). vol. 111, No. 3. pp 290-301.

Tehrani, B.H. (1988) *Chemical Stabilisation of Whaka terrace Loess Christchurch.* Msc Thesis, (Eng. Geology) University of Canterbury.

Tonkin, P.J.; Runge, E.C.A. and Ives, D.W. (1974) *A study of Late Pleistocene Loess deposits, South Canterbury, New Zealand.* Part 2: *Paleosols and their Stratigraphic Implications.* Quarternary Resesarch, vol 4. pp 76-84.

Trangmar, B.B. (1976) *Soil Resource Survey of the Sumner region, Port Hills, Canterbury.* Msc. Thesis, University of Canterbury.

Trangmar, B.B. (1978) *Relationships Between Soils, Regolith and Erosion on the Port Hills, Canterbury, New Zealand.* Paper presented at a Seminar on "Slope Stability and Urban Development". Dept. of Extension studies, University of Canterbury, 24-25 February.

Trangmar, B.B and Cutler, E.J.B. (1983) *Soils and erosion of the Sumner region of the Port* *hills, Canterbury, New Zealand.* N.Z Soil Bur. Bur. Soil Surv. Rep. 70.

Trangmar, B.B. (in prep.) *Soil Survey of the Port Hills, Canterbury, New Zealand.* N.Z Soil Bur. Soil surv. Rep.

Weaver, S.; Sewell, R. and Dorsey, C. (1985) *Extinct Volcaoes: A Guide to The Geology of Banks Peninsula.* Geological society of N.Z. Guidebook no. 7. 48 p.

Wild, L.J. (1919) *Note on the composition of the so called loess at Timaru.* Trans. N.Z. Inst. vol 51. pp 286-288.

Wilms, T.R. (1979) *An Investigation into Aspect Related Erosion Forms in a Valley in the Port Hills, Banks Peninsula.* Unpublished M. Ag. Sc. thesis, University of Canterbury.

Winterkorn, H.F. (1975) *Soil Stabilisation* Ch 8 in: "Foundation Engineering Handbook", Winterkorn and Fang, eds. Van Nostrand. pp 312-336.

Yetton, M.D. (1986) *Investigation and Remedial methods for Subsurface Erosion control in Banks Peninsula Loess.* Msc Thesis, (Eng. Geology) University of Canterbury.

Young, D.J. (1964) *Stratigraphy and Petrography of North-East Otago Loess.* N.Z J. of Geol. and Geophys, vol 7. pp: 839-63.

Appendix A: In-situ Bulk and Dry Density

A.1 Apparatus

1) Stainless steel sampling tubes: Diameter = 35.5 mm. Length = 170 mm. Edge at one end is sharpened to assist in soil penetration.

2) Sampling Tube Driver: Consists of a sliding weight which is used to drive the sampling tubes into the soil.

3) Callipers.

A.2 Method and Calculations

1) After field collection the tubes are placed into plastic bags in order to maintain field water content.

2) Weigh the tube and soil at natural moisture content.

3) Dry the soil in a 105° oven for at least 12 hours.Weigh the tube and dry soil.

4) Measure the length of the soil in the tube. Calculate the volume of the soil (V).

5) Extrude the soil and weigh the tube.

6) Subtract the weight of the tube from the soil + tube weights to determine the weight of the soil at natural water content: M, and dry state: Ms. Determine the natural water content of the soil (Appendix C.2).

7) Calculate the In-situ bulk and dry densities using the following formulas:

$$\text{Bulk Density (kg/m}^3\text{)} = (\,M(g) \div V(cm^3)\,) \times 1000$$

$$\text{Dry Density (kg/m}^3\text{)} = (\,Ms(g) \div V(cm^3)\,) \times 1000$$

Appendix B: Soil Description Terminology

B.1 Terminology

1) Fragipan: Compact, massive or near massive horizons. When dry they are brittle, and have the appearance of being strongly cemented, but the apparent cementation dissapears on moistening.

2) Gley Mottling

Gleying is a chemical process by which the Fe^{3+} ion (found in iron oxides) is reduced to Fe^{2+}. This occurs when soils become anaerobic due to water logging by a high water table usually caused by impeded drainage. (Mclaren and Cameron, 1993). Usually gleying produces grey zones which are bordered by yellow, brown or red zones .

3) Gammation

Often occurs in the fragipan of yellow-grey earths. Water penetrates the widely spaced cracks which seperate the fragipan prisms. Water soaks into the soil next to the cracks. Close to the cracks, the soil gets leached of iron and Gleying takes place. As a result a grey colour pattern is formed around the cracks. In areas that have climates that are close to semi-arid conditions, gammation tends to be faint (subgammate). In sub-humid conditions they are usually coarse and distinct (gammate), while in the transition to humid regions they often have a band of reticulate veins at the top of the fragipan (net-gammate), suggesting a change to wetter conditions after the fragipan was formed.

4) Peds are natural, relatively permanent aggregates, separated from each other by voids or natural surfaces of weakness (Mclaren and Cameron, 1993).

B.2 Soil Description Terminology

1) Soil Material

Soil material was described according to the system showed in Figure B.1.

2) Soil Structure Terminology

In this project, soil structure was described according to soil science nomenclature in which the grade, size, and type of soil structure is given (Tab. B.2 - 3).

3) Soil Horizon Classification

In this project, genetic soil profile labels based on generally accepted soil science terminology are used to designate the different soil horizons. A description of the genetic impications of the different soil profiles are described below:

A Horizon: A dark coloured horizon containing organic matter mixed with mineral matter. It is a zone of maximum biological activity and eluviation (removal of materials dissolved or suspended in water).

B Horizon: Horizon of accumulation of suspended material from A which often includes clay minerals, or iron and organic matter.

C Horizon: Weathered parent material. Sometimes a zone of calcium carbonate accumulation. The subscript: x is used to indicate the occurence of a fragipan

B.2 Soil Classification

Yellow-grey earths are distinguished from one another by the extent to which leaching and weathering has taken place as controlled by the moisture regime (Mclaren and Cameron, 1993). Table B.1 is a comparison of the morphological features of the Yellow-grey earth sub-groups which form in the gifferent moisture regimes. Soils in the hydrous sub-group belong to the yellow-grey to yellow-brown soil group.

	Dry-subhydrous	Subhydrous	Dry-hydrous	Hydrous
Approx. Rainfall:	530 mm	640 mm	690 mm	1000 mm
Fragipan	Sub gammate	gammate	gammate to net	No fragipan
Gley Mottling (above fragipan)	none/faint	weak	strong	none/very little
Depth to Fragipan (cm)	30-50	30-60	40-70	30 cm to compact horizon

Table B.1: Morphological features of the different yellow-grey earth sub-groups.

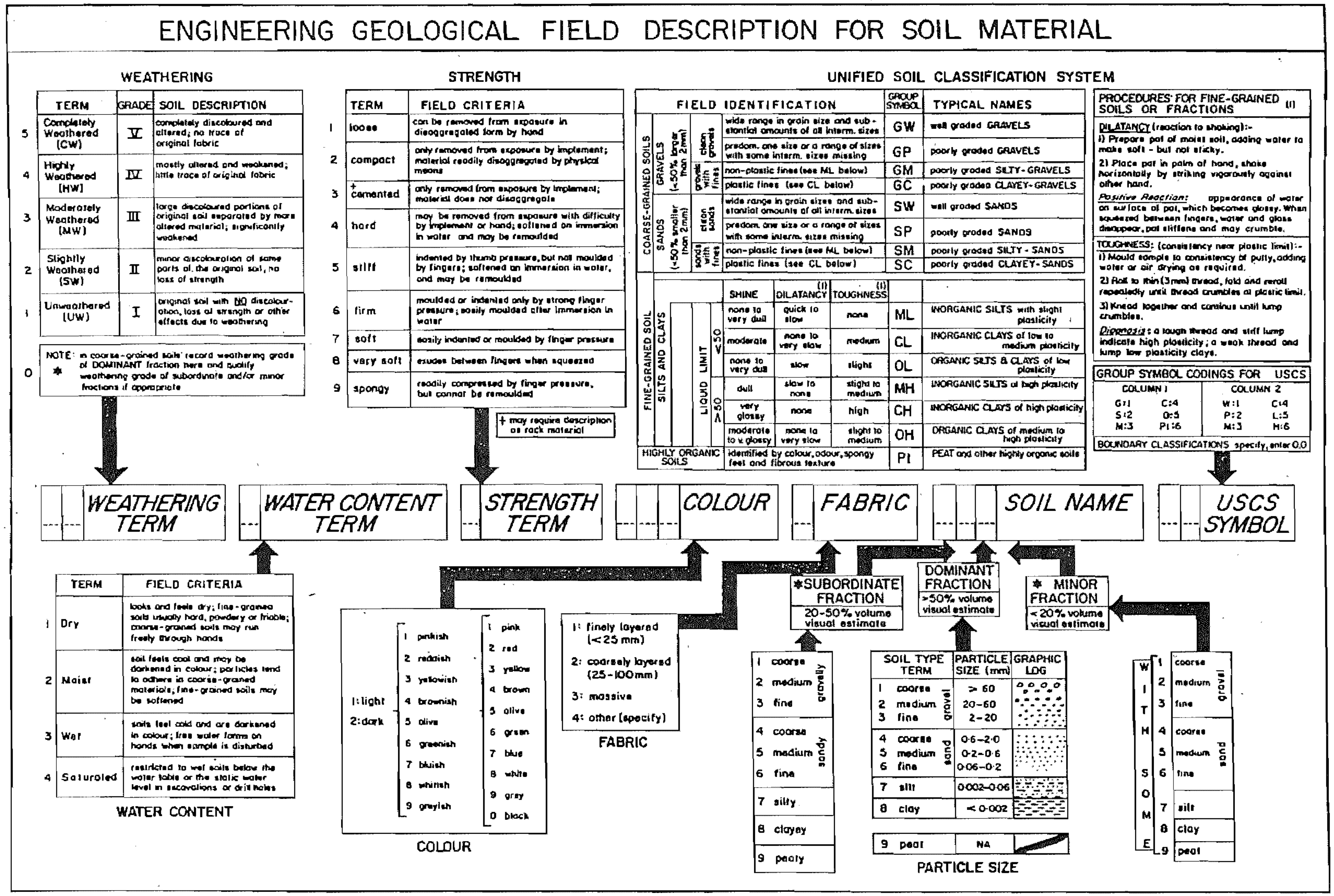


Figure B.1: Soil material classification system (after Bell and Pettinga, 1984).

APEDAL No observable aggregation; without a definite orderly arrangement of natural planes of weakness.	
single grained	when disturbed the soil breaks into individual primary particles (possibly with coatings that adhere directly to them).
massive[1]	when disturbed the soil breaks into masses which may be easily crushed into small fragments or may be strongly coherent.
PEDAL Observable natural planes of weakness that define the surface of peds in some part or all of the soil.	
weakly developed	poorly formed indistinct weakly coherent peds that are barely observable in places. When disturbed the soil breaks into a few entire peds, many broken peds and much unaggregated material.
moderately developed	well formed moderately durable peds which are evident but not distinct in undisturbed soil. When disturbed the soil breaks down into a mixture of many distinct entire peds, some broken peds and a little unaggregated material.
strongly developed	durable peds that are quite evident in undisplaced soil, adhere weakly to one another and withstand displacement, separating cleanly when the soil is dusturbed. Disturbed soil material consists very largely of entire peds and little or no unaggregated material.

Table B.1: Soil structure grade. (after Mclaren and Cameron, 1993).

	structure type		
size classes	columnar prismatic	blocky nut	platy granular crumb
very fine	<10	<5	<1
fine	10-20	5-10	1-2
medium	20-50	10-20	2-5
coarse	50-100	20-50	5-10
very coarse	>100	>50	>10

Table B.2: Soil structure size classes. (after Mclaren and Cameron, 1993).

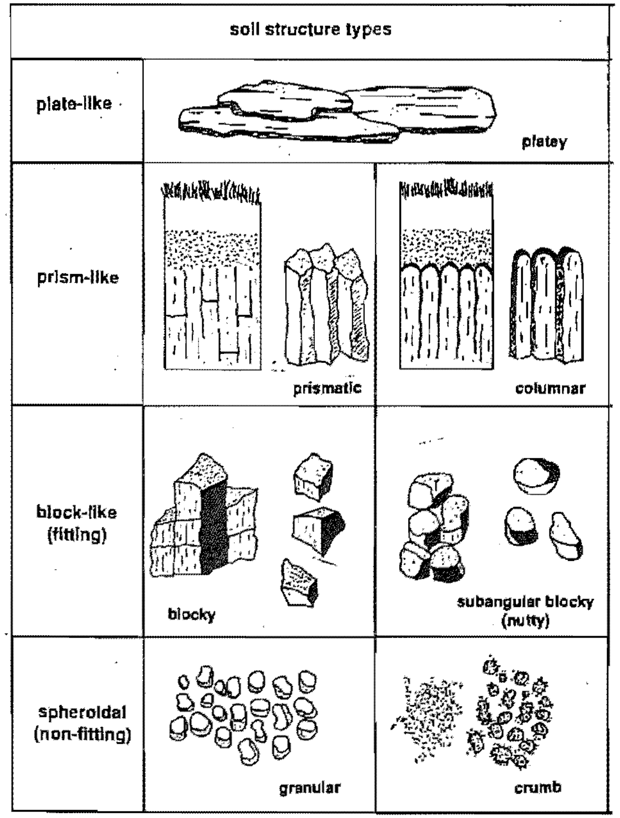


Table B.3: Soil structure type. (after Mclaren and Cameron, 1993).

Appendix C: Miscellaneous Soil Tests

C.1 Water Content

(NZS 4402: 1986 Test 2.1: Determination of the water content.)

The water content is defined as the amount of water that is contained in the voids of the soil. The amount of water contained in the voids of a soil in it's natural state is called the natural water content. The water content is the ratio of the mass of water (Mw) to the mass of solids (Ms) in the soil (Craig, 1992). All water contents in this project are quoted as percentages.Multiplication by 100 converts the water content ratio into a percentage:

$$w\% = (Mw \div Ms) \times 100\%$$

C.2 Dry Density/Water Content Relationship

NZS 4402: 1986 Test 4.1.1

Soils at a range of different water contents are compacted under standard conditions in a container of known volume and mass to give a range of dry densities. A graph of the water content / dry density relationship makes it possible to estimate the maximum dry density and the corresponding optimum water content.

C.3 Linear Shrinkage

NZS 4402: 1986 Test 2.6 Determination of the linear shrinkage.

The soil (at liquid limit) is placed into a mould of standard length and air dried. The extent of shrinkage is measured. Linear shrinkage is calculated from:

$$LS = (1 - L(dry) \div L(mould)) \times 100\%$$

where: **L(dry)** = length of dry specimen and **L(mould)** = internal length of mould (150 mm).

Appendix D: Grain Size Analysis

D.1 Grain Size Terminology

In this project, 'Clay' is the name given to mineralogical material finer than 2 µm regardless of it's composition. The term 'Clay mineral' is defined by Eslinger and Pevear (1988) as hydrous aluminium phyllosilicate "minerals which normally dominate the fine (< 2 µm) fraction of rocks and soils".

Soil scientists, Geologists and Engineers use different grain size analysis terminology schemes. Table D.1 is a comparison of the different grain size divisions most commonly used in New Zealand.

Diameter of Soil Particle (mm)			
Class	**Soil Science**	**Geology**	**Engineering**
Gravel	> 2	> 2	> 2
Sand	0.02-2	0.0625-2	0.06-2
Silt	0.002-0.02	0.0039-0.0625	0.002-0.06
Clay	< 0.002	< 0.0039	< 0.002
Source	International Society of Soil Science	Folk Andrews and Lewis (1970)	Craig (1992)

Table D.1 A comparison of the major grain size classification schemes used by workers in the fields of soil science, geology and Engineering in New Zealand.

The engineering classification scheme is very similar to the geological scheme except that the clay boundary is 0.002 mm rather than 0.0039 mm. Although soil science uses the same clay boundary as engineering, it has a considerably different Silt/Sand boundary.

There is no sharp universal boundary between the particle size of clay minerals and non clay minerals. However, there is a general tendency for clay minerals to be smaller than 2µm (Grim, 1968). Also, most non-clay minerals are larger than 2 µm. Therefore 2 µm would seem to be the most logical upper boundary of the clay size grade. Therefore, where possible, all of the grain size distributions described in this project will be in terms of the engineering classification scheme. Results from papers using different classification schemes will require translation.

In this project, the "phi" scale is often used to describe particle size. The phi scale is a geometric scale in which each value is 1/2 or 2 x the millimetre value of the next. The grain size distribution graphs (see D.3) show the relationship between the mm and phi scales.

D.2 Method

The method used to determine grain size distribution was from Lewis (1984): "Pipette Analysis of Mud", pg: 88-99. The following is a summary of the procedure that was followed:

1) Use a sample splitter to randomly select 30g of soil (at natural water content) that will be representative of the bulk sample.
2) Fully disaggregate the soil. Put the soil into a mortar. Add distilled water and 20 ml of 50 g per litre sodium hexamataphosphate. Crush the soil with (rubber-gloved) fingers until it appears that the soil is desegregated.
3) Separate the sand fraction from the mud (silt and clay fraction). Wet sieve the soil/water slurry through the 4 phi sieve.
4) Pour the mud/water slurry into a 1 litre measuring cylinder. Add enough distilled water to fill the measuring cylinder up.
5) Dry the material retained on the sieve (sand). Dry sieve and determine the grain size distribution of the sand. The dry sieves typically used in this project were the: 4, 3.5, 3, 2.5, 2, 1.5, 1, 0.5 and 0 phi sieves. Put the material which passes through the 4 phi sieve (silt and clay that was not washed through during the wet sieving process) into the measuring cylinder.
6) Carry out a Pipette analysis.

D.3 Results

Figures D.1-10 are the grain size analysis curves that are reffered to in the text.

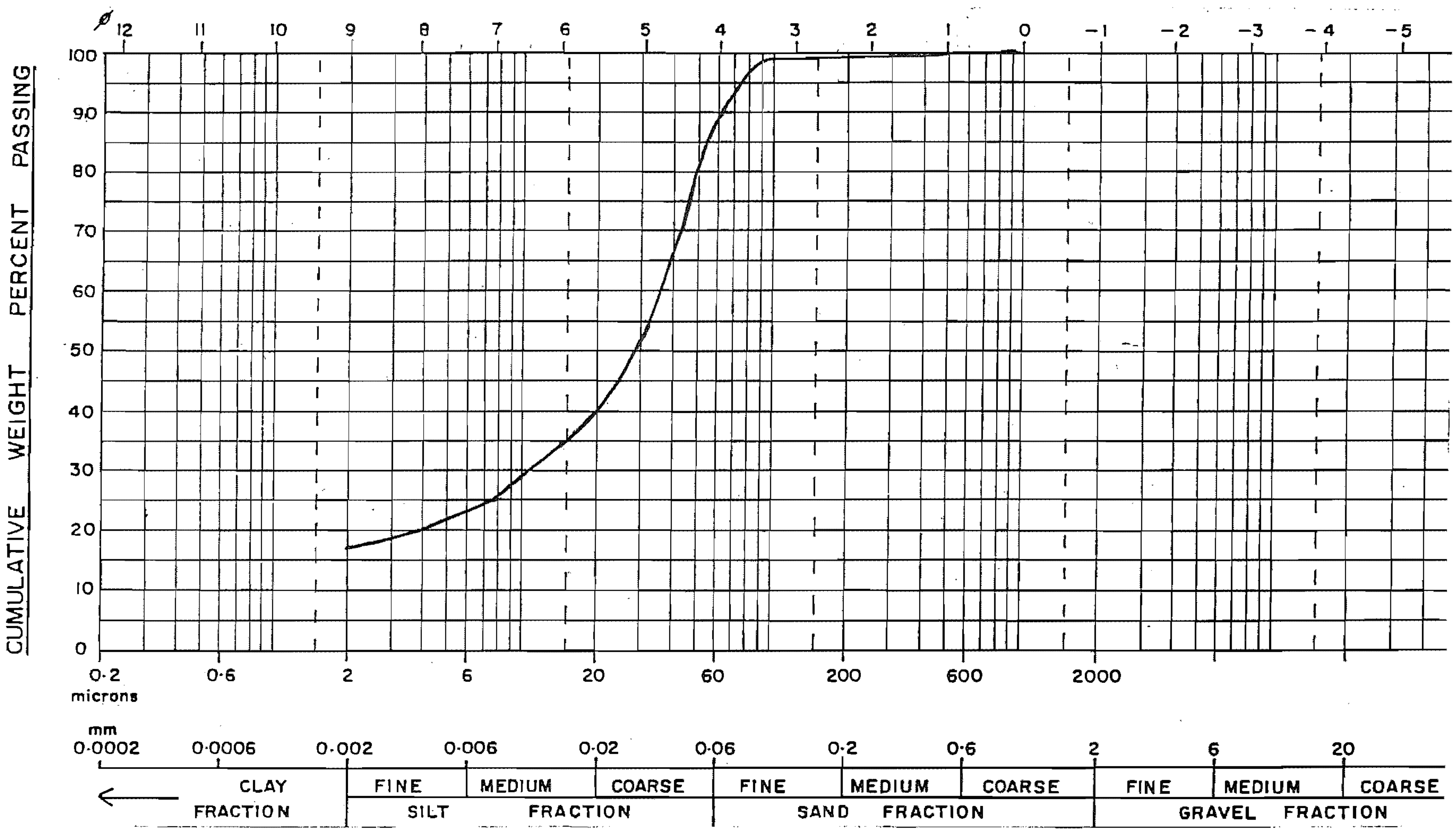


Figure D.1: Grain size distribution curve for C horizon loess from the Ahuriri site.

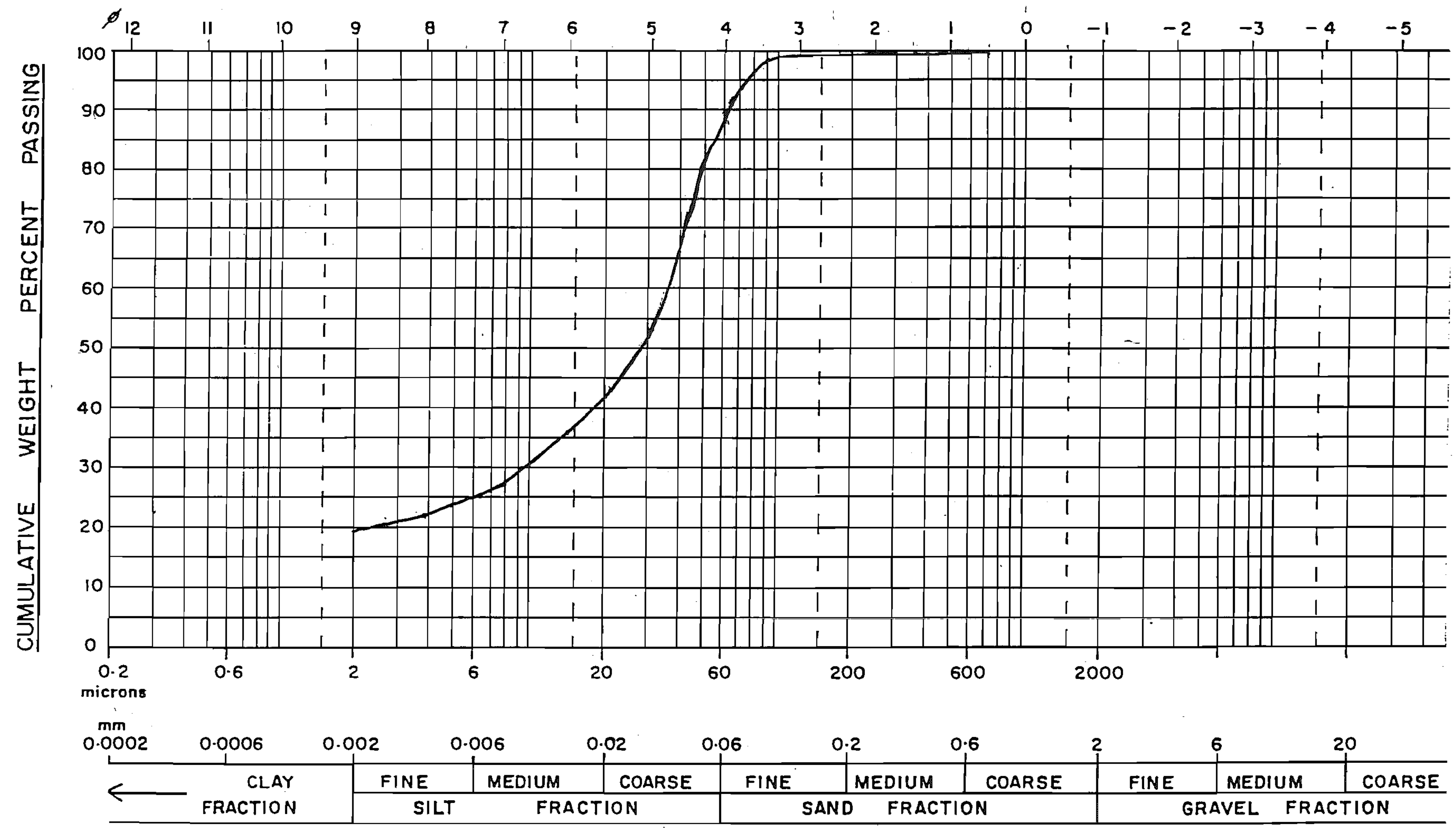


Figure D.2: Grain size distribution curve for C horizon loess from the Gebbies Valley site.

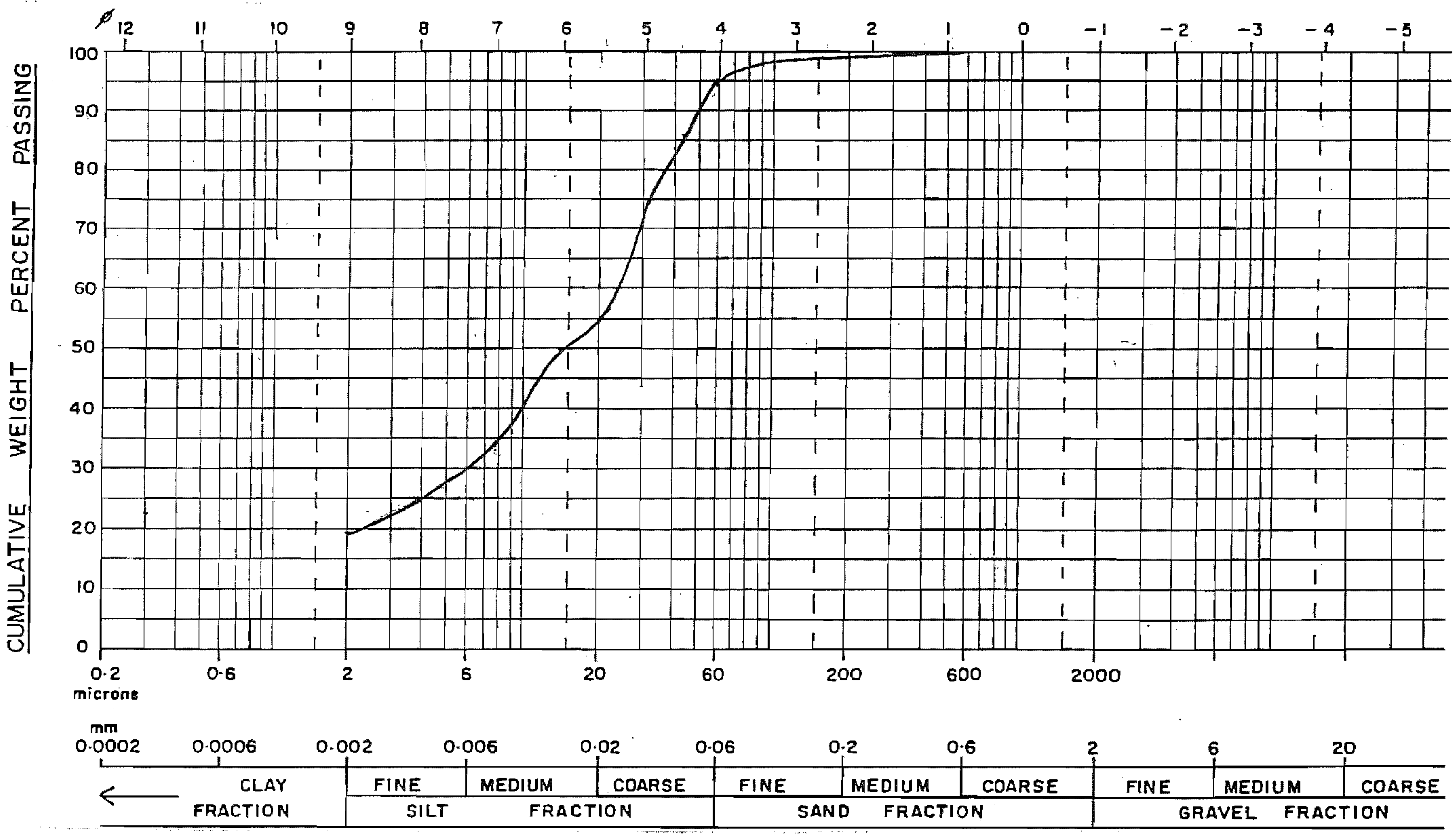


Figure D.3: Grain size distribution curve for C horizon loess from the Timaru site.

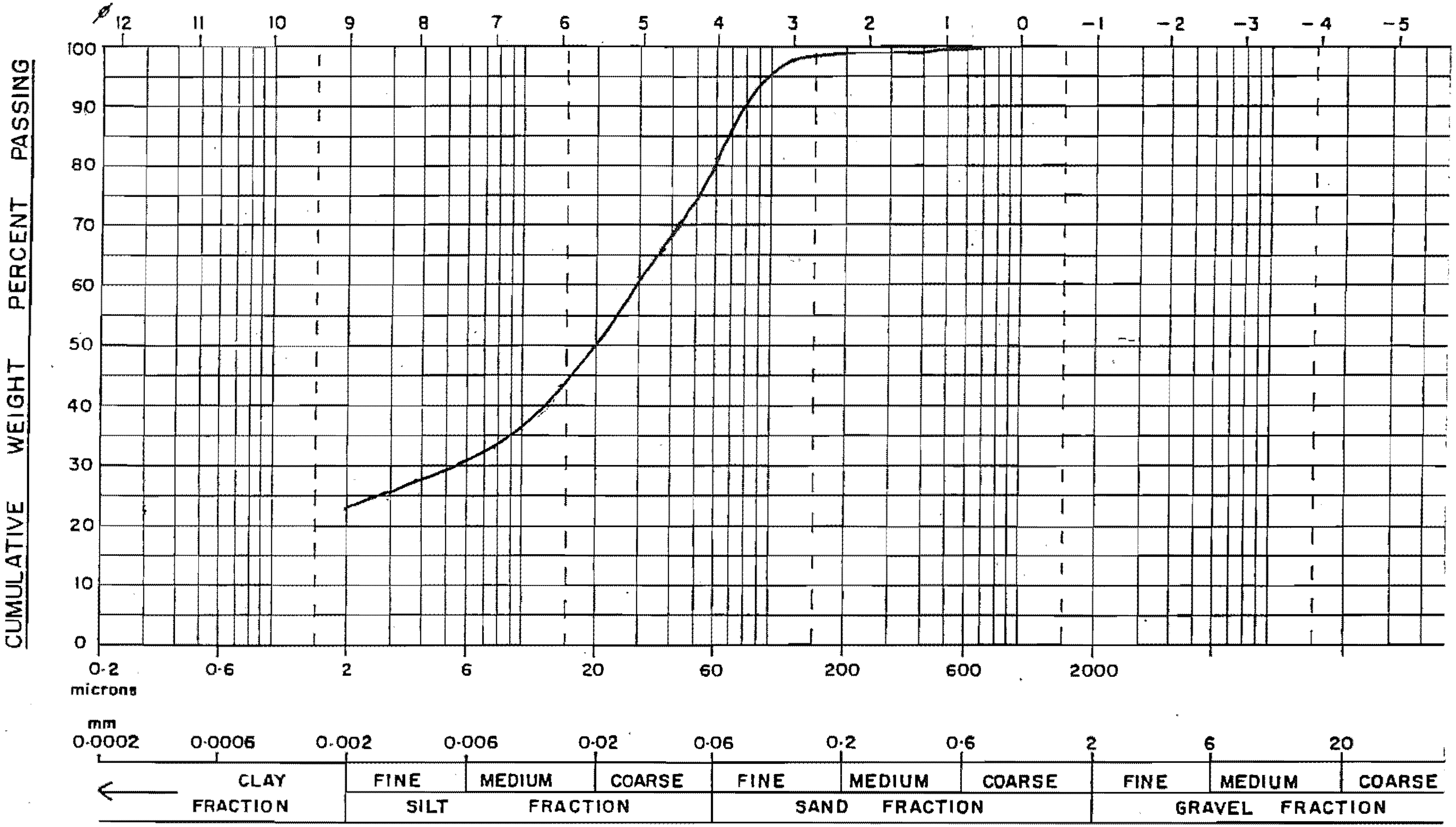


Figure D.4: Grain size distribution curve for C horizon loess from the Taiko site.

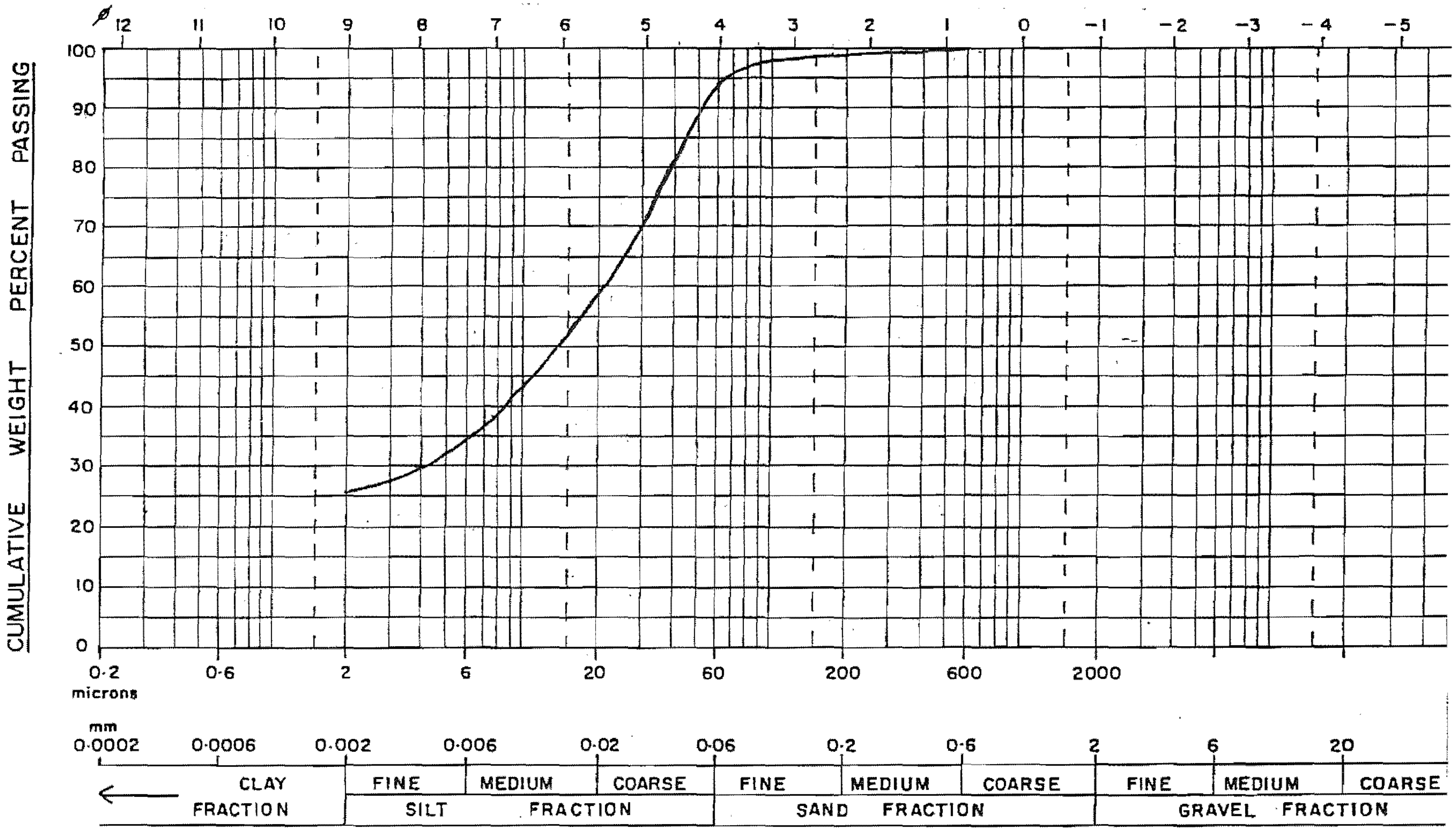


Figure D.5: Grain size distribution curve for C horizon loess from the Wither Hills site.

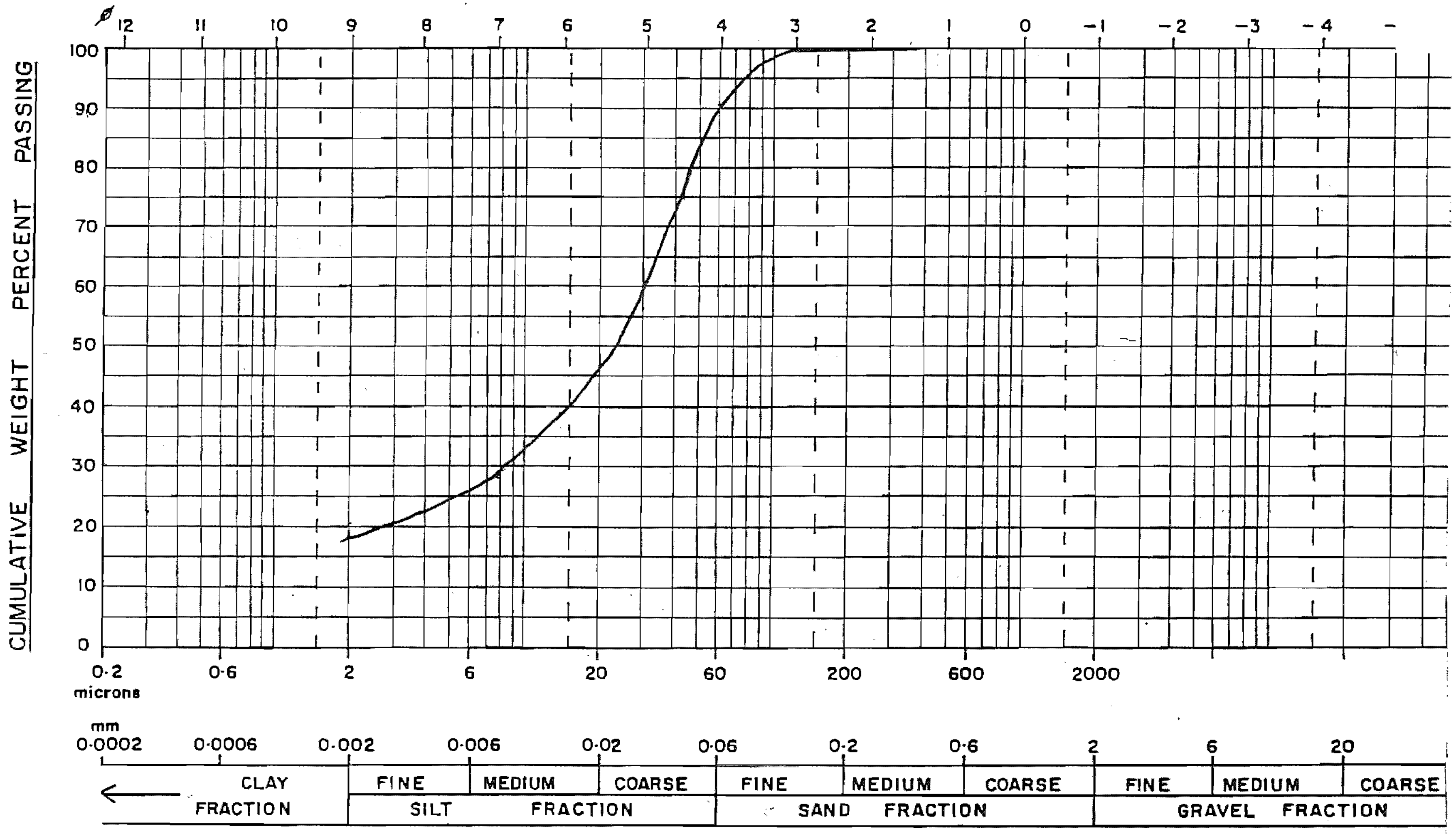


Figure D.6: Grain size distribution curve for C horizon loess from the Barrys Bay site.

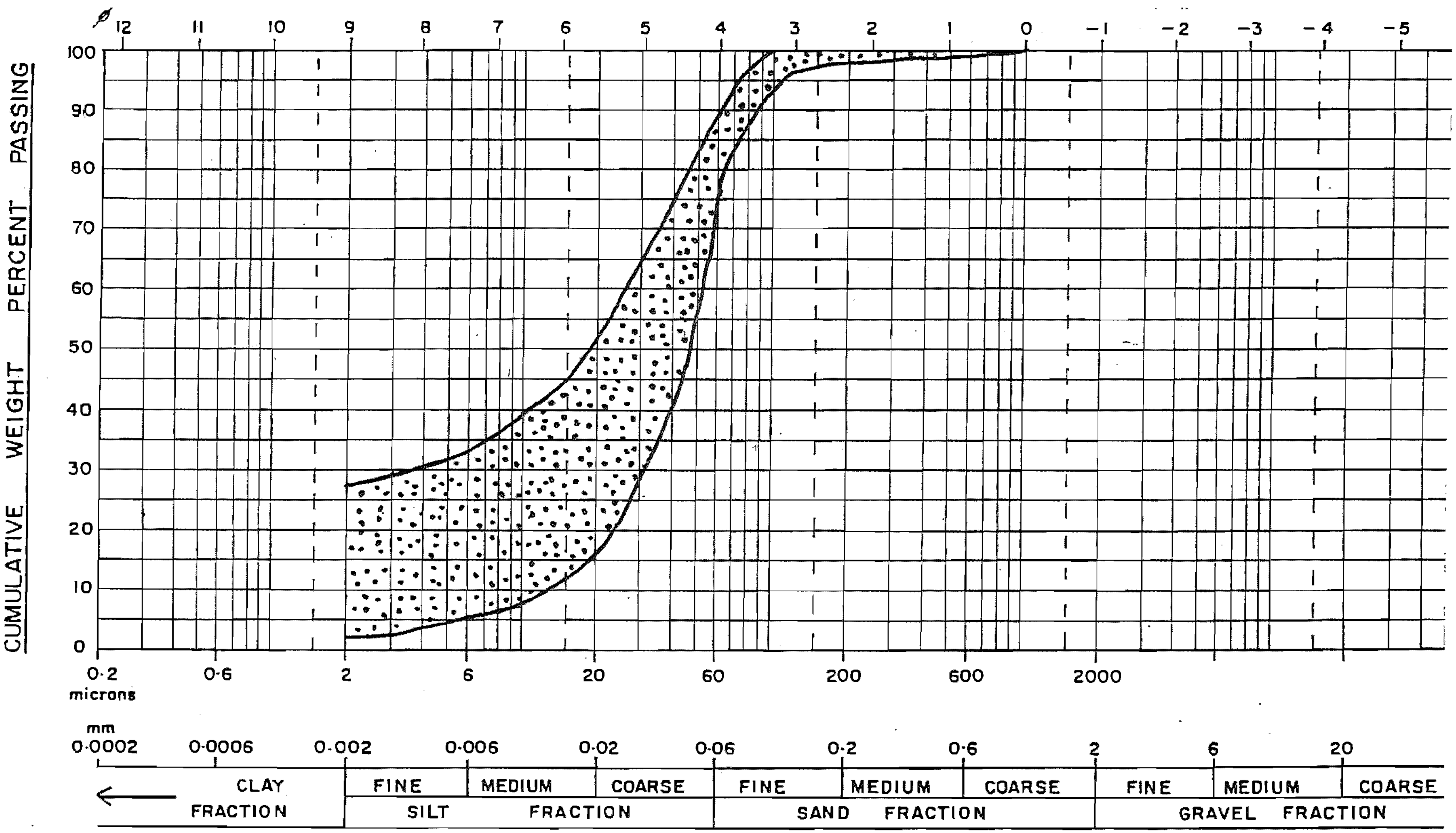


Figure D.8: Grain size distribution envelope for Ahuriri quarry loess.

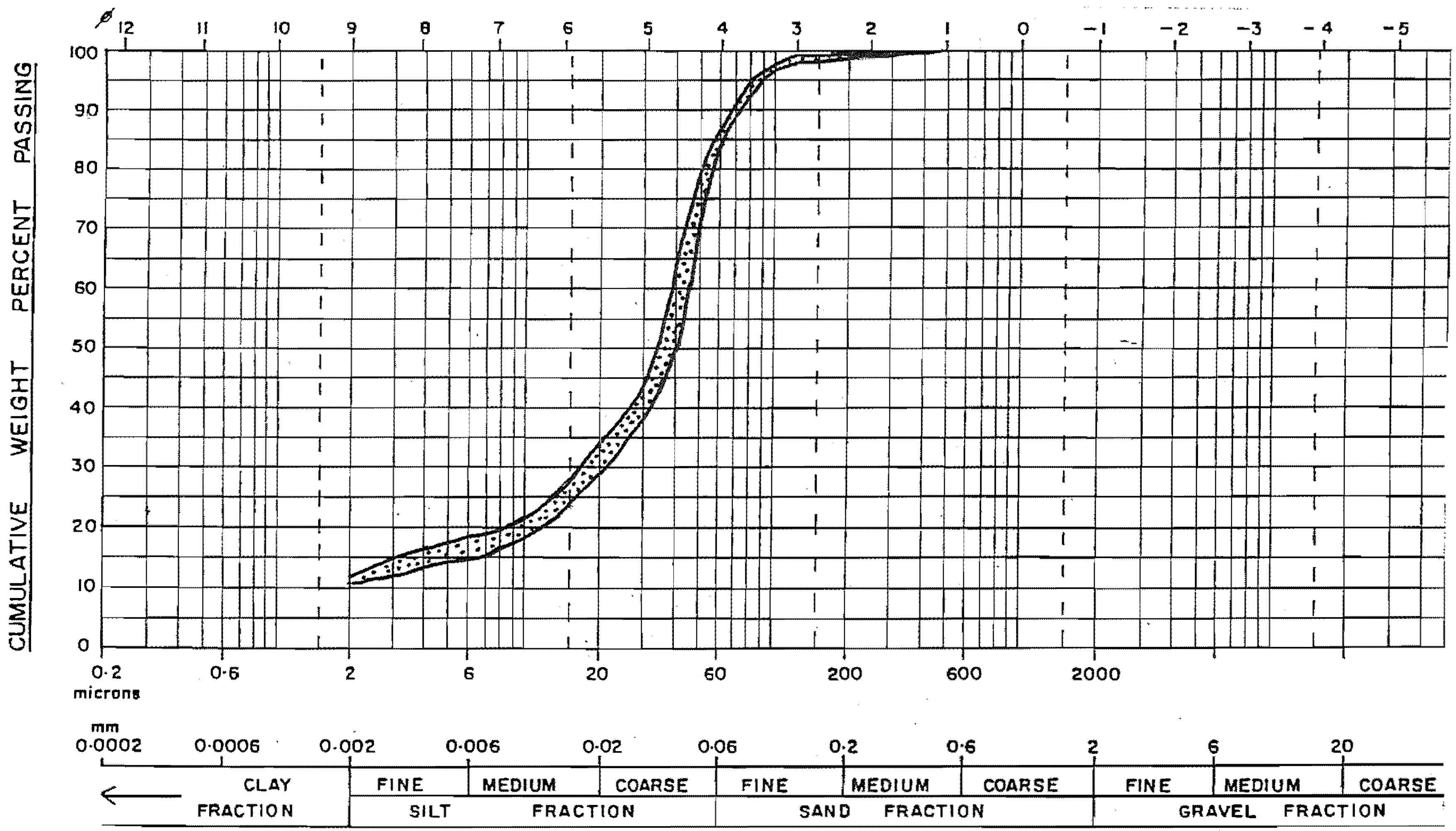


Figure D.9: Grain size distribution envelope for untreated Ahuriri quarry loess.

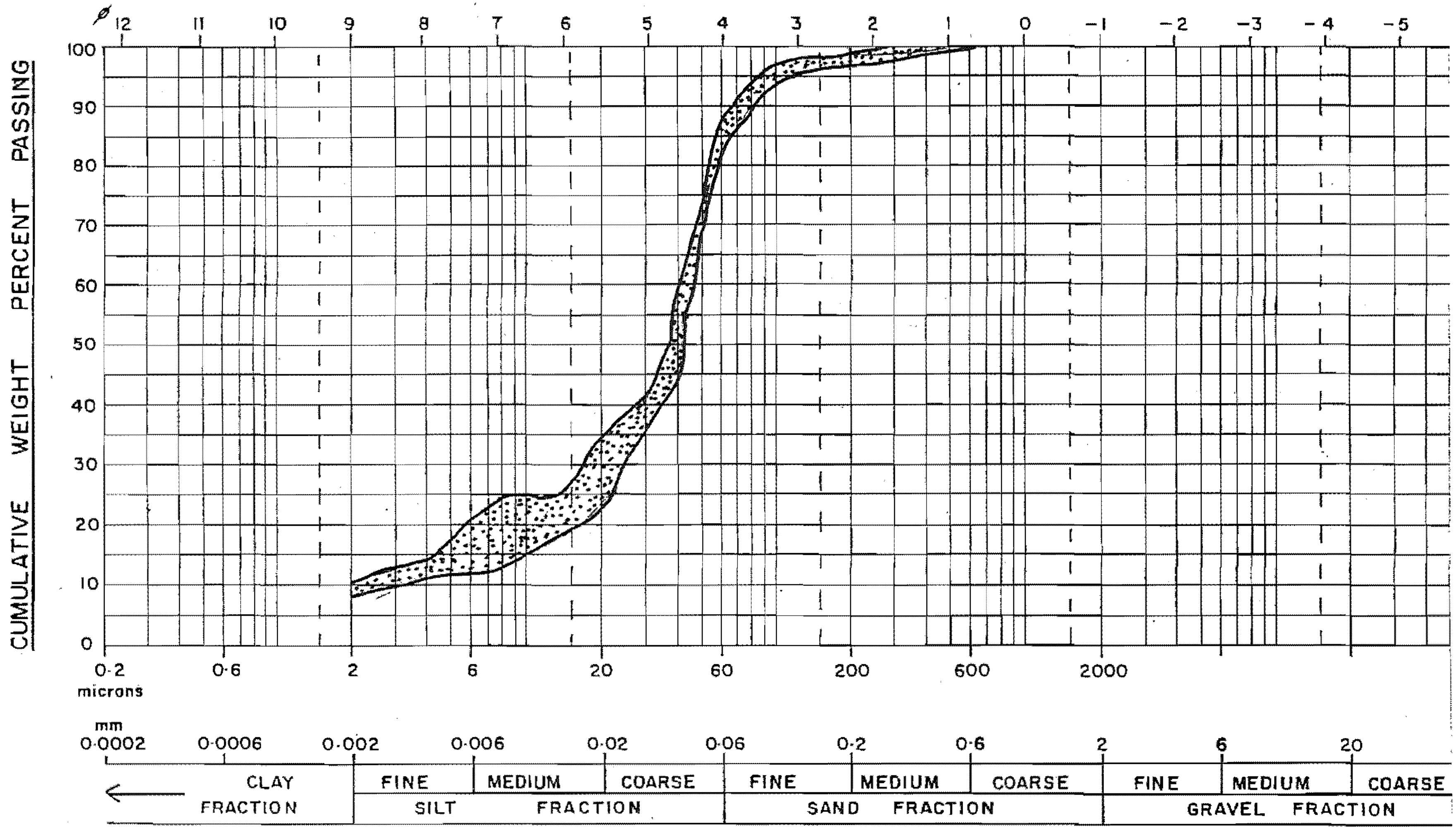


Figure D.10: Grain size distribution envelope for 2.5% quicklime treated Ahuriri quarry loess.

Appendix E: Falling Head Permeability Test

Soil with a water content at about the plastic limit was compacted into single layers in a proctor compaction cell. The layer took up approximately a third of the compaction cell. The compactive effort used to compact the soil was the same as the compactive effort used to compact a single layer in the standard compaction test (see Appendix C.2). The length of the specimen (L) and the cross sectional area of the cell (A) were recorded. To saturate the sample, the remaining two thirds of the proctor mould are filled with water and left for two days. After soaking, a coarse filter was placed at each end of the cell and a stand pipe of known internal area (a) was connected to the top of the cell. The stand pipe was filled with water to a height (h_0) above a fixed datum. The height of water in the stand pipe decreased as the water is left to flow through the soil in the proctor mould. The coefficient of permeability (k) is measured from the expression:

$$k = \{(a.L) \div (A.t_1)\} \times \{\ln (h_0 \div h_1)\}$$

Where: $\mathbf{t_1}$ is the time after which the final water height $\mathbf{h_1}$ is measured.

Readings were taken at regular intervals until the values from consecutive readings became consistent; sometimes this took up to five days to happen.

Appendix F: Dispersion Tests

F.1 Modified British Standards Crumb test

(Based on: BS 1377: Part 5: 6.3: 1990)

F.1.1 Method

A crumb preserved at natural water content, and about 4-6 mm in diameter is dropped into a 50ml beaker of distilled water. The beaker is left for ten minutes. The extent to which the clay fraction goes into colloidal suspension (disperses) is observed. A "Dispersion Class" (after Yetton 1986) is allocated to indicate the extent of dispersion.

Dispersion Class 1: No reaction. Crumb may slake and run out on the bottom of the beaker. However, there is no sign of cloudy water caused by colloids in suspension.

Dispersion Class 2: Slight reaction. Slight cloud in water near the surface of the crumb.

Dispersion Class 3: Moderate reaction. Easily recognisable cloud of colloids in suspension around the sample.

Dispersion Class 4: Strong reaction. Colloidal cloud virtually obscures the whole bottom of the beaker and in extreme cases the whole beaker becomes cloudy.

In this project, intermediate crumb classes i.e 1.5, 2.5 and 3.5 were assighned when the soil exhibited dispersion between the classes given above. All results given are the average of five tests. The crumb test results on the same soil were found to be highly reproducable with a maximum variation of 1 crumb class.

F.2 Modified British Standards Dispersion Test

(Based on: BS 1377: Part 5: 6.4: 1990.)

F.2.1 Apparatus

1) 1000 ml measuring cylinder.

2) 500 ml conical Flask.

3) A 63 μm sieve.

4) The apparatus used for grain size analysis (see Appendix C.2)

5) Wash bottle

F.2.3 Method

The method given below is based on the test procedure in the British standards 1377: part 5: 1990, Section 6.4: "Dispersion method".

1. Carry out a grain size analysis (see Appendix D) to determine the clay % of the soil.
2. Sieve another sample (weighing about 30 g) of the same soil tested in 1 (at natural moisture content) through a 2 mm sieve.
3. Put the soil into the flask and add 100 ml of distilled water and agitate sufficiently to bring the soil into suspension. Poor the suspension into a 1 litre measuring cylinder.
3. Perform a pipette analysis as for the full grain size analysis but only take two subsamples. Take the first subsample (A) after 20 seconds at a depth of 10 cm to determine the total sample mass (sand plus silt plus clay). After 8 hours take another sample (B) to determine the clay fraction mass. (B ÷ A) × 100% gives the clay percentage in the soil/water solution.

% Dispersion = (clay % in soil/water solution ÷ clay % from grain size analysis)*100%

F.2.4 Results

The full results of all dispersion % tests carried out are shown in Table F.1.

Site	Horizon	Clay %	Mass (A)	Mass (B)	100(A/B)	Dispersion %
Ahuriri	Cx	23.5	0.508	0.059	11.6	49
	C	17.3	0.469	0.069	14.7	85
Gebbies Valley	B	22.4	0.376	0.031	8.2	37
	Cx	23.7	0.473	0.072	15.2	64
	C	18.8	0.504	0.073	14.5	77
Timaru	B2	21	0.479	0.076	15.9	76
	Cx	22.5	0.505	0.09	17.8	79
Taiko	B2	26.6	0.43	0.089	20.7	78
	C	23.2	0.476	0.095	20	86
Wither Hills	B2	32	0.453	0.109	24.1	75
	Cx	26.8	0.431	0.102	23.7	88
	C	25.7	0.492	0.109	22.15	86
Barrys Bay	B1	20.8	0.329	0.029	8.8	42
	C	17.8	0.468	0.068	14.5	81

Appendix G: Pinhole Tests

G.1 Modified British Standards Pinhole Test

Modified after BS 1377: Part 5: 1990, section 6.2

G.1.1 Introduction

This test is very similar to the pinhole test carried out in most of the international literature. It is based on the test developed by Sherard (1976). A very similar method can also be found in the Australian Standards: AS 1289.C8.3-1984. The New Zealand standards do not contain a pinhole test.

G.1.1 Apparatus:

1) Glass head tank at a height of about 1.2 m.

2) Flexible plastic tubing to connect the test components.

3) Inlet valve to control water flow.

4) Pinhole test apparatus.

5) 5 litre measuring bucket.

6) Pea Gravel.

7) Electric drill.

G.1.2 Method

1) Obtain Tube samples from the field. The sample should be approximately 50 mm long. The tubes used to obtain the samples had a diameter of 35.5 mm and were 100 mm long (the extra length being required for the attachment of the sample tube driver) Maintain insitu water content until testing.

2) Trim the sample so that it is approximately 50 mm long and flush with one of the ends. With a Calliper, measure and record sample length.

3) Drill a 1mm diameter hole through the centre of the sample the sample. A truncated conical depression is countersunk in the centre of the sample. Set the sample up in the apparatus.

4) Open the inlet valve until a steady rate of flow is obtained with a head of 50 mm. Follow the instructions given on the flow chart (Fig. G.3). Use Table G.1 to determine the pinhole erosion class. E1 is the most erosive, NE1 is the least erosive.

Note: The British standard classification classes are provided in brackets in Table G.1. These classes represented different grades of "dispersion": D1 and D2 were describe as being "dispersive" while the ND classes were described as being non-dispersive. However, in this project, for reasons provided in Chapter 2 the word "dispersive" was substituted with the word "erosive".

Erosion Class	Head	Test time for given head	Final flow rate through specimen	Cloudiness of flow at end of test	Hole size after test	Description
--	mm	min	mL/s		mm	
E1 (D1)	50	5	1-1.4	Pale	>2	Highly Erodible
E2 (D2)	50	10	1-1.4	Cloudy-Misty	>1.5	Erodible
NE4 (ND4)	50	10	0.8-1	Misty	<1.5	Potentially Erodible
NE3 (ND3)	180	5	1.4-2.7	Slight	>1.5	Potentially Erodible
	380	5	1.8-3.2	-	-	Potentially Erodible
NE2 (ND2)	1020	5	>3	Clear	<1.5	Non-erodible
NE1 (ND1)	1020	5	<3	Crystal clear	1	Completely erosion resistant

Table G.1 Pinhole erosion classification table. Modified after British standards BS 1377: Part 5: 1990. The Bracketed classes are from the British standards.

G.2 Quantitative Pinhole Test

This test is based on the quantitative pinhole test developed by Trangmar and schafer (1981). Trangmar and Schafer used an "erosion index" to define the magnitude of erosion. The erosion index was defined as : the increase in volume (ml) of the cavity which would be formed in a 50 mm long specimen by distilled water flowing at 3 ml/sec from a 1 mm diameter inlet, after 5 litres has flowed. The conditions given in the above definition were met by the method given below, so the term "erosion index" was also used to describe the erosion of samples in the pinhole tests carried out in this project.

G.2.1 Apparatus

The same as Appendix G.1, except the head control tube was not used. The pipe giving access from the pinhole apparatus to the head control tube was blocked (usually with insulation tape). A 5 litre bucket was used to determine when 5 litres of water had flowed through the pinhole.

G.2.2 Method

1. Follow the set-up procedure given in G.1.2.
2. Run water through the tube at a flow rate of 3ml/sec. Use the bucket to collect the eroded soil plus water after it has flown through the sample.
3. Stop water flow after 5 litres of water has passed through the sample. At 3 ml/sec this should take approximately 28 minutes.
4. Shake the bucket used to collect the water/sediment to get all of the eroded sediment into suspension. Take a random 1 litre sample of the water/sediment suspension. Dry it in a 105 °C oven. Weigh the sediment and multiply by 5 to obtain the total weight of eroded sediment. Given the dry density of the soil it is possible to calculate the eroded volume.

G.2.3 Calculations

Erodibility index = mass of eroded soil ÷ dry density of soil

G.2.4 Results

The raw values of the test results are shown in Tables G.2 and G.3.

Site	Horizon	Effluent Volume (l)	Dry Density g/cm3	Initial Volume (cm3)	Initial Mass (g)	Eroded Soil (g)	Erosion Index
Wither	C	5	1.66	52.24	86.72	12.5	7.53
		5	1.66	54.52	90.5	38.15	22.98
		5	1.66	42.82	71.08	8.1	4.88
	B2	5.525	1.76	49.97	87.95	0.35	0.2
		5	1.76	50.48	88.84	0.15	0.09
		5	1.76	50.68	89.2	0.55	0.31
	Cx	5	1.65	47.19	77.86	2.7	1.64
		5.75	1.65	49.35	81.43	0.45	0.27
Gebbies	B	5	1.57	50.48	79.25	0.85	0.54
		5	1.57	49.73	78.08	6.2	3.95
		5	1.57	49.49	77.7	1.05	0.67
Barrys	C	5	1.65	51.83	85.52	0.7	0.42
		5	1.65	51.51	84.99	0.4	0.24
		5	1.65	51.98	85.77	0.25	0.15
	B2	5	1.63	49.03	79.92	0.4	0.25
		5	1.63	51.11	83.31	0.75	0.46
		5	1.63	50.72	82.67	0.15	0.09

Table G.2: Quantitative pinhole test results

Sample	Horizon	Water	Density (g/cm3)	Initial Volume (cm3)	Initial mass (g)	Eroded Soil (g)	Erosion Index
Taiko	C	tap	1.82	48.36	88.0152	0.43	0.24
		tap	1.82	47.11	85.7402	0.18	0.1
	B2	tap	1.73	49.17	85.0641	0.24	0.14
		tap	1.73	49.03	84.8219	0.35	0.2
	C	distilled	1.82	49.23	89.5986	1.93	1.06
		distilled	1.82	51.27	93.3114	1.28	0.7
		distilled	1.82	51.41	93.5662	1.01	0.55
		distilled	1.82	49.53	90.1446	7.2746	4
Timaru	Cx	tap	1.83	50.76	92.8908	10.44	5.7
		tap	1.83	49.21	90.0543	10.19	5.57
		tap	1.83	48.66	89.0478	3.78	2.07
		tap	1.83	48.58	88.9014	8.58	4.69
	B2	tap	1.79	48.12	86.1348	1	0.56
		tap	1.79	51.59	92.3461	4.7	2.63
Ahuriri	C	tap	1.55	49.49	76.7095	43	27.74
		tap	1.55	52	80.6	19.3	12.45
		tap	1.55	49.59	76.8645	17.37	11.21
		tap	1.55	52.6	81.53	26	16.77
		tap	1.55	49.47	76.6785	40.33	26.02
		distilled	1.55	51.83	80.3365	39.71	25.62
		distilled	1.55	45.6	70.68	39.94	25.77
		distilled	1.55	40.64	62.992	38.5	24.84
		distilled	1.55	49.69	77.0195	33.42	21.56
		distilled	1.55	51.83	80.3365	8.14	5.25
		distilled	1.55	45.6	70.68	30.07	19.4
Gebbies	Cx	tap	1.67	39.67	66.2489	28.65	17.16
		tap	1.67	45.45	75.9015	18.23	10.92
		tap	1.67	46.64	77.8888	12.87	7.71
		tap	1.67	30.09	50.2503	19.97	11.96
	C	tap	1.59	46.38	73.7442	36.45	22.92
		tap	1.59	45.69	72.6471	43.6	27.42
		tap	1.59	47.18	75.0162	48.64	30.59
		tap	1.59	49.23	78.2757	29.54	18.58

Table G.3 Pinhole test results

Appendix H: Slake Tests

H.1 Confined Uniaxial Expansion Test

(Method adapted from ISRM, 1981 by Yetton, 1986))

H.1.1 Apparatus

1) 25 mm long open metal ring with a 35.5 mm diameter.

2) Two porous disks. Thickness: mm. Diameter: mm.

3) Metal disk. Thickness: mm. Diameter: mm.

4) Water Bath deep enough to hold sample.

5) Expansion measuring device with Transducer attached.

6) Computer capable of recording results from Transducer data.

7) Data recording software.

H.1.2 Method

1) Obtain an undisturbed tube sample (35.5 mm diameter) from the field. Extrude a portion and place it in the metal ring. Trim the ends of the soil sample so that it is trim with the ends of the ring.

2) Dry the sample in a 40° oven for at least 24 hours.

3) Place the sample on a porous disk in the water bath. Cap the sample with a porous disk. Put the metal disk on top of the porous disk. Put the end of the expansion measuring device on top of the metal disk.

4) Turn the Computer on. Turn on any of the connections between the computer and the transducer. Zero the Transducer (read software manual for more information).

5) Slowly pour distilled water into the water bath until the water level is mid way up the porous capping disk.

6) Run the test until no further expansion takes place. This may take up to three days.

7) Save the test data to disk and print the resulting time versus expansion graph

H.1.3 Calculations

The following formula is used to calculate uniaxial expansion (U.E):

$$U.E = [\{ L(\text{final}) - L(\text{initial}) \} \div L(\text{initial})] \times 100\%$$

Where: **L(final)** is the length of the soil sample after expansion. **L(initial)** is the length of the sample before it is placed into the water bath (25 mm).

H.1.4 Results

Test results are shown in the uniaxial expansion against time graphs shown in figures H.1 to H.13.

H.2 Quantitative Slake Test

H.2.1 Apparatus

Figure C.x shows the test set-up. A description of the apparatus is given below:

1) Sartorius 2354 scale: Maximum measurable weight: 1000g. Accurate to 0.01g. Base attachment allows the weight of samples hanging off the bottom of the scale to be determined.

2) Basket: Attached to the base of the scale. Used to hold the mesh (see below). Made of light weight wire.

3) Mesh: 4cm by 4cm square copper mesh with 2mm by 2mm mesh openings. Used to hold the soil sample.

4) 1 litre glass beaker

H.2.2 Method

Tests were carried out on both remoulded and undisturbed samples. Point 3) applies to undisturbed samples.

1) Collect a 35.5 mm tube sample from the field. Extrude the sample and cut it down to a length of about 40 mm.

4) Allow to air dry in a 40 degree oven for at least one day. Weigh the sample to an accuracy of 0.001g. This is the initial dry weight of the sample: M(initial).

5) Fill the 1 litre beaker to the 600 ml mark.

6) Place the mesh in the basket. Attach the basket to the sartorius 2354 scale. Place the basket in the beaker so that the mesh sits approximately 50 mm below the surface of the water. Record the weight of the mesh in the water without the sample Place the sample on top of the mesh.

7) Leave the sample in the water for 15 minutes, then remove sample from the water and dry in a 105 degree oven. Weigh the dry sample to determine M (final). If sample completely disintegrates before 15 minutes, record the time at which the sample disintegrates.

H.2.3 Calculations

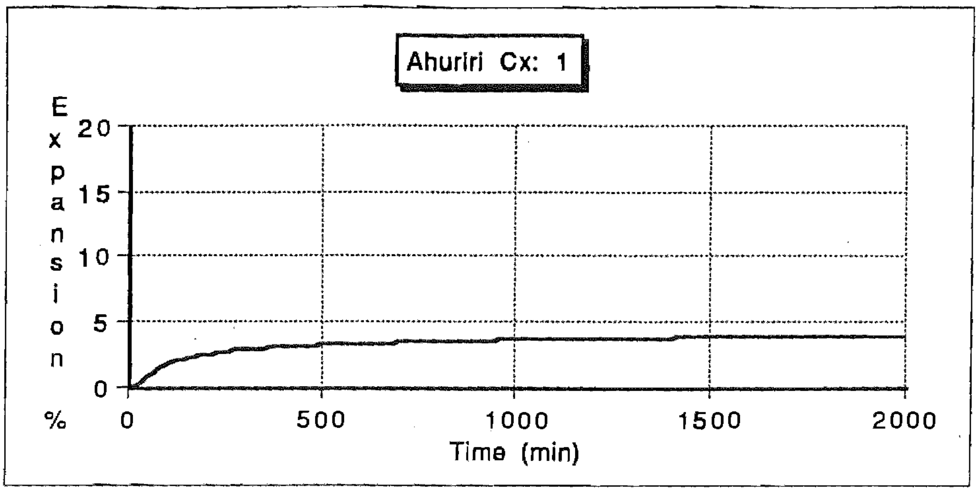
1) The degree of slaking is represented by the "slake rating" (S.R). The calculation used to determine the S.R is shown below:

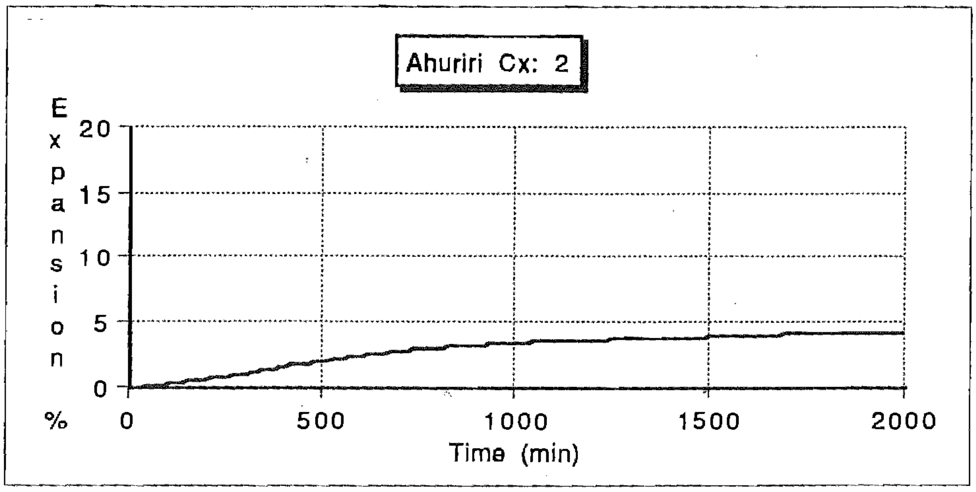
S.R = (M(initial) - M(final))g / test time(min)

Where: **time(min)** is either 15 minutes if the sample is still coherent at the end of the test or the time at which the sample is destroyed. **M(initial)** is the dry mass of the soil ball before immersion in water. **M(final)** is the dry mass of the soil after the 15 minutes testing period. If the soil ball fails before the end of the testing period, then M(final) = 0.

Site/Horizon	M (Initial) (g)	M (Final) (g)	Time (min)	Slake Rate (g/min)
Barry/C	77.611	0	5.5	14.6
Barry/B2	75.735	27.63	15	3.2
Timaru/Cx	75.936	46.091	15	1.99
Timaru/B	79.595	58.521	15	1.4
Gebbies/B	78.036	62.956	15	1.01
Gebbies/C/1	67.13	0	11.5	5.8
Gebbies/C/2	72.84	0	5	14.6
Gebbies/C/3	62.67	0	8	7.8

Table H.1: Quantitative slake test results.





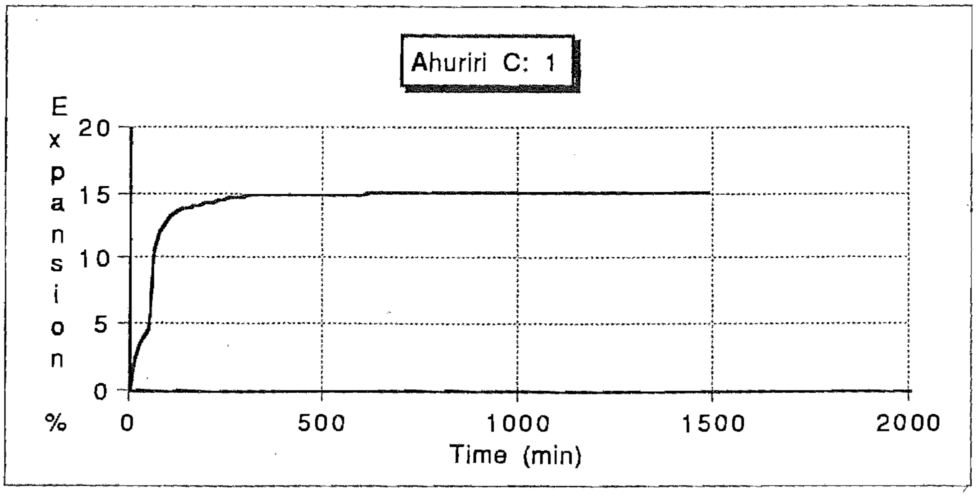
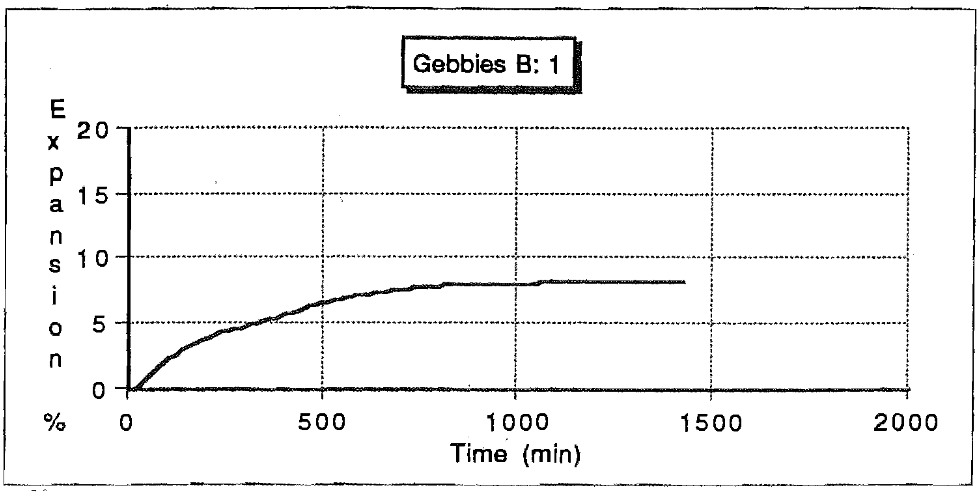
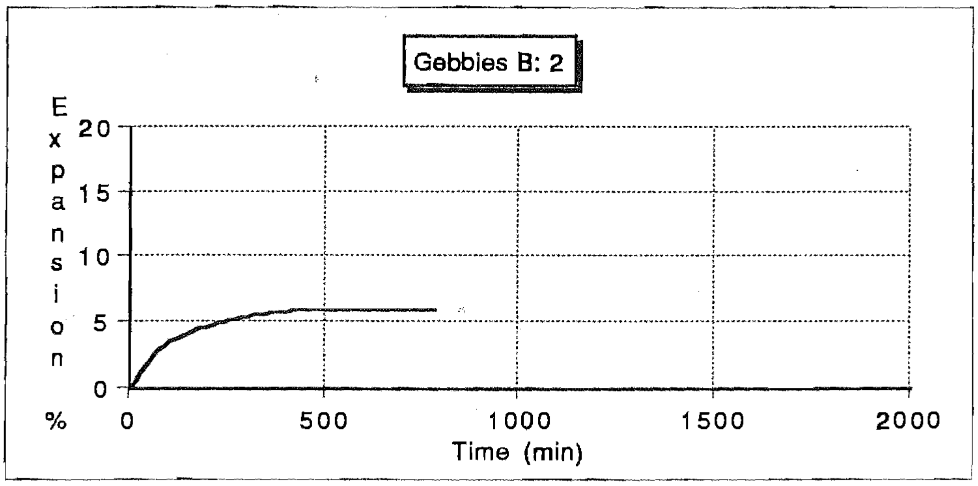


Figure H.1: Uniaxial expansion results. Site, horizon and test number given in the title of each graph





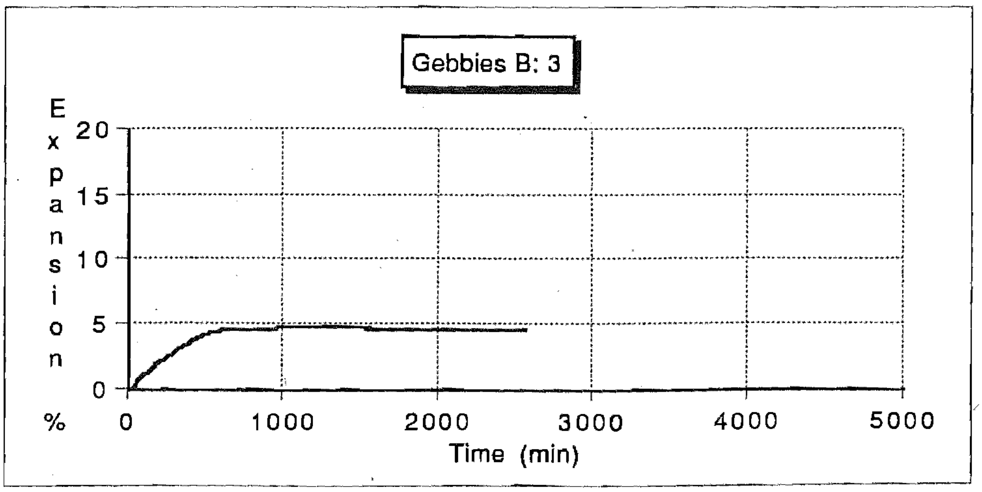
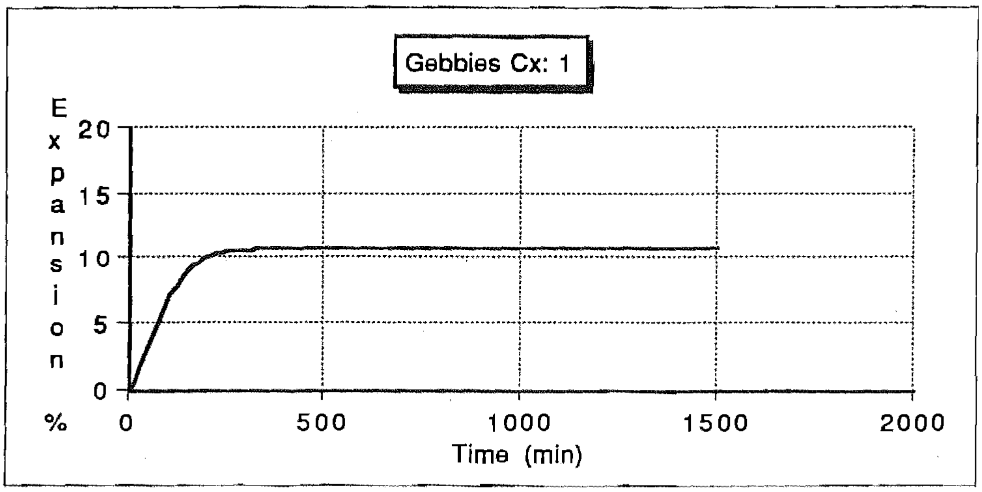
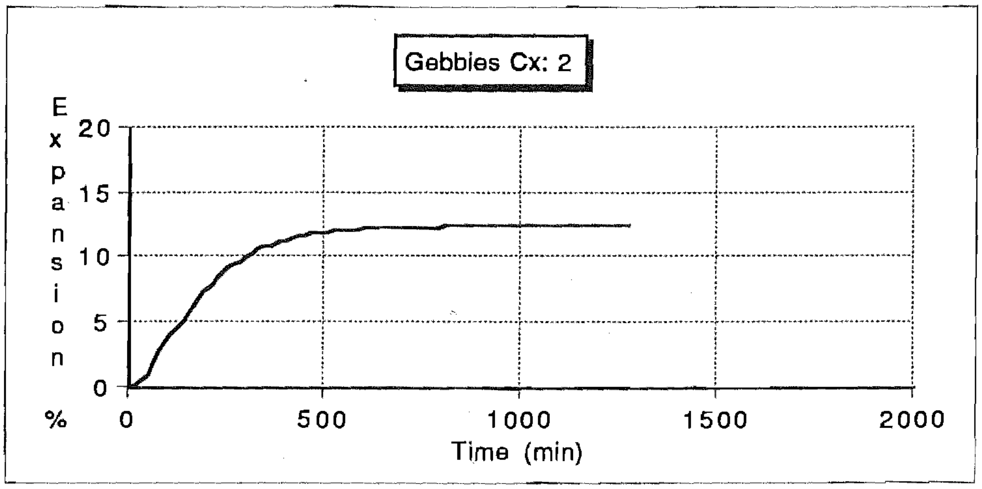


Figure H.2: Uniaxial expansion results. Site, horizon and test number given in the title of each graph.





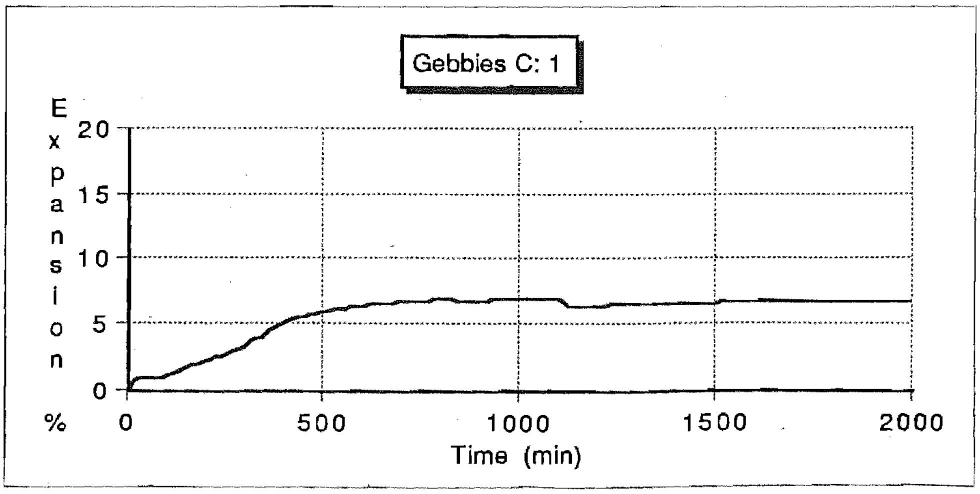
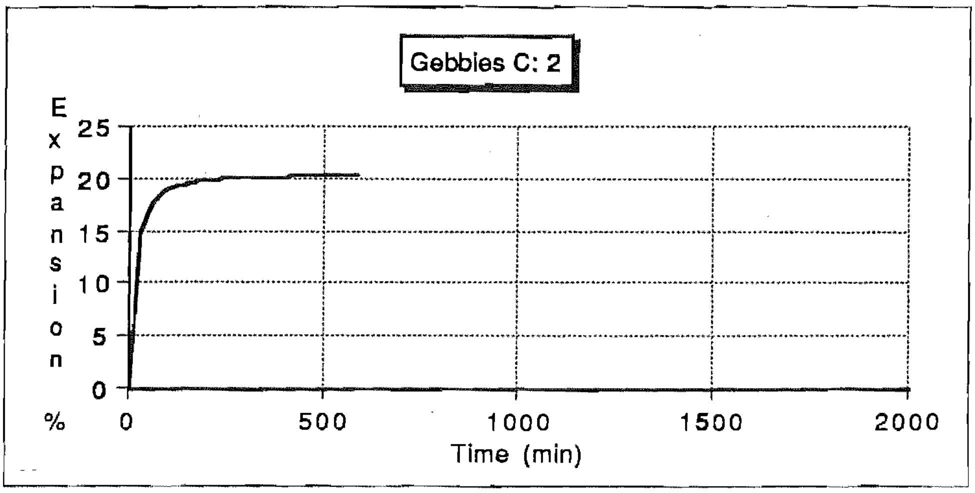
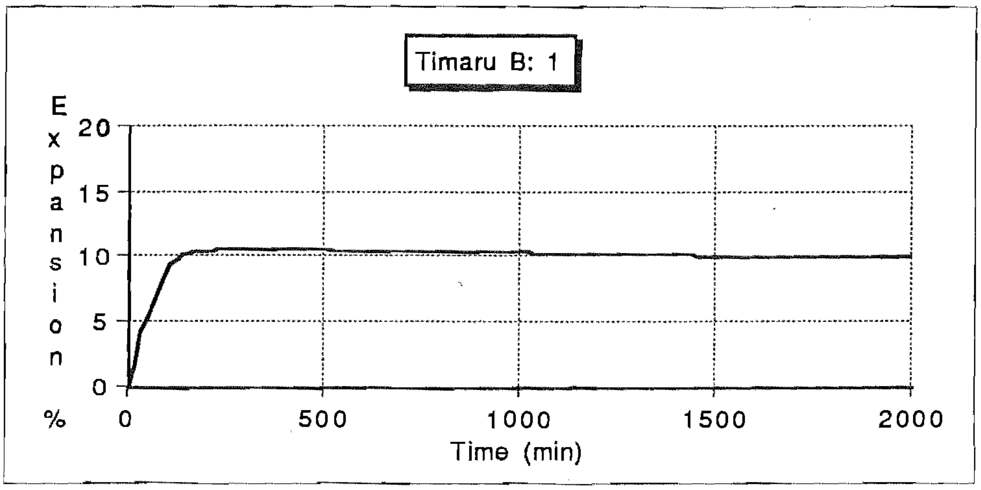


Figure H.3: Uniaxial expansion results. Site, horizon and test number given in the title of each graph.





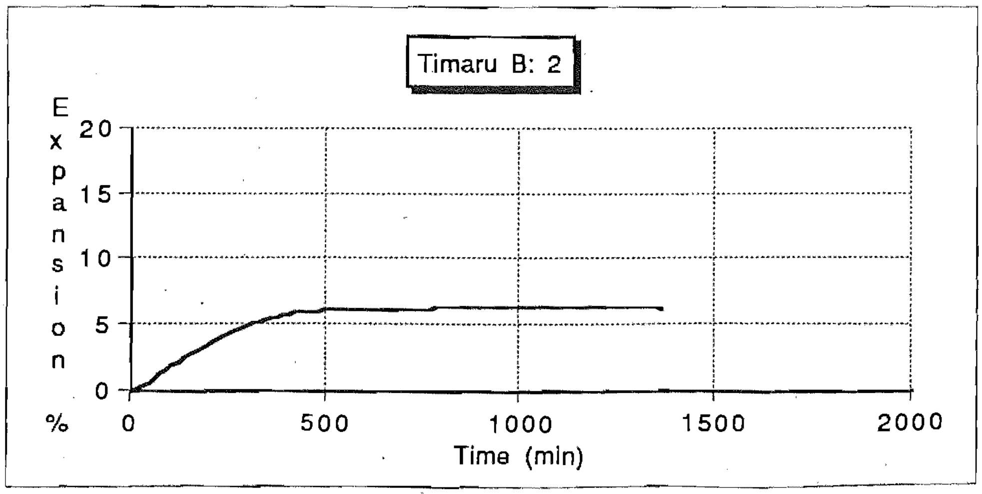
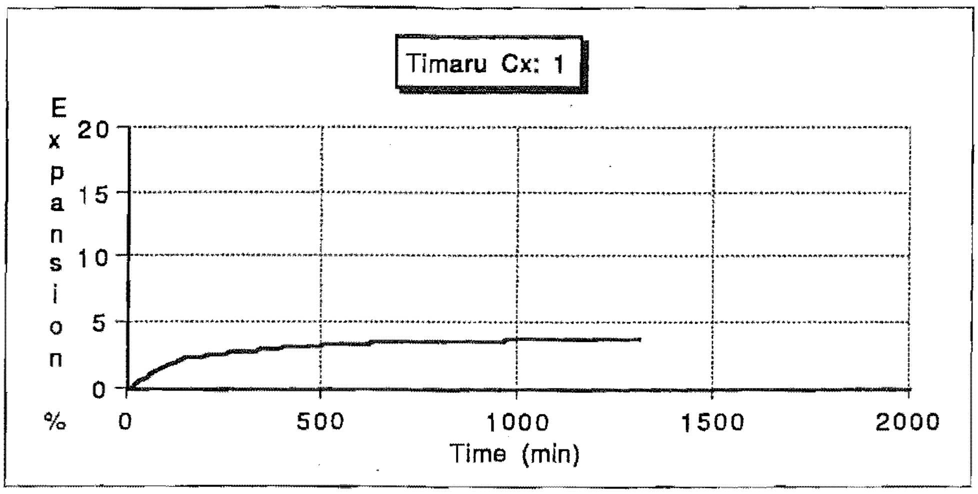
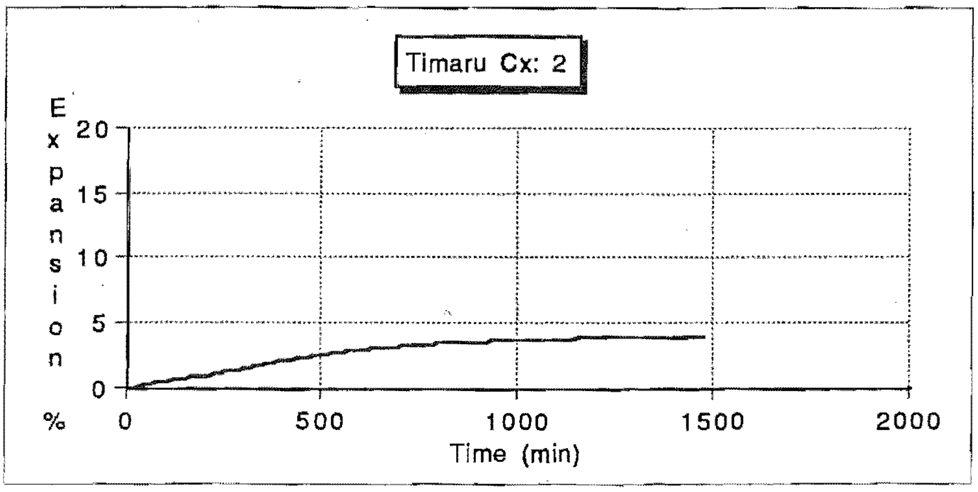


Figure H.4: Uniaxial expansion results. Site, horizon and test number given in the title of each graph.





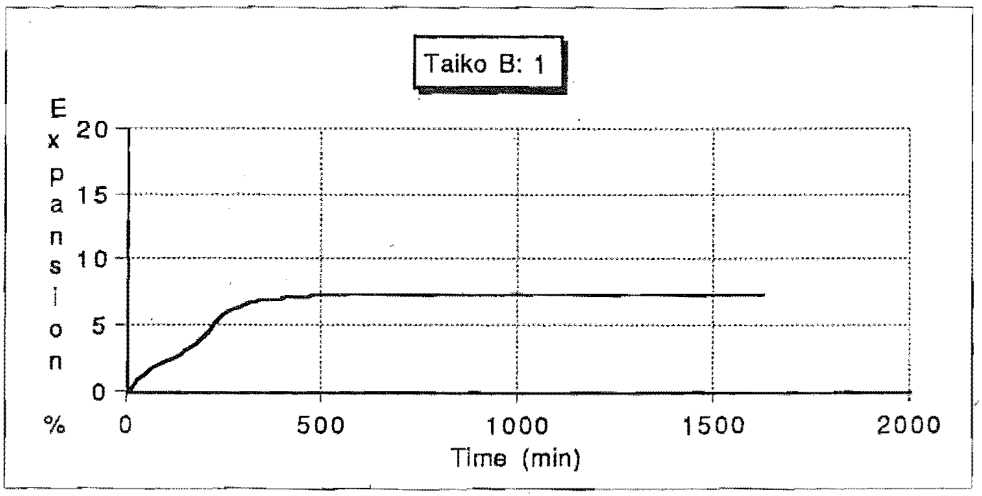
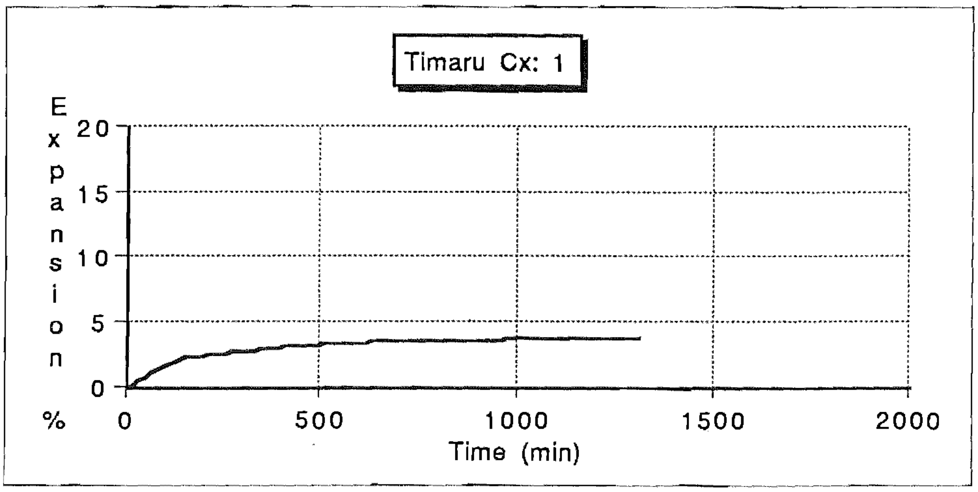
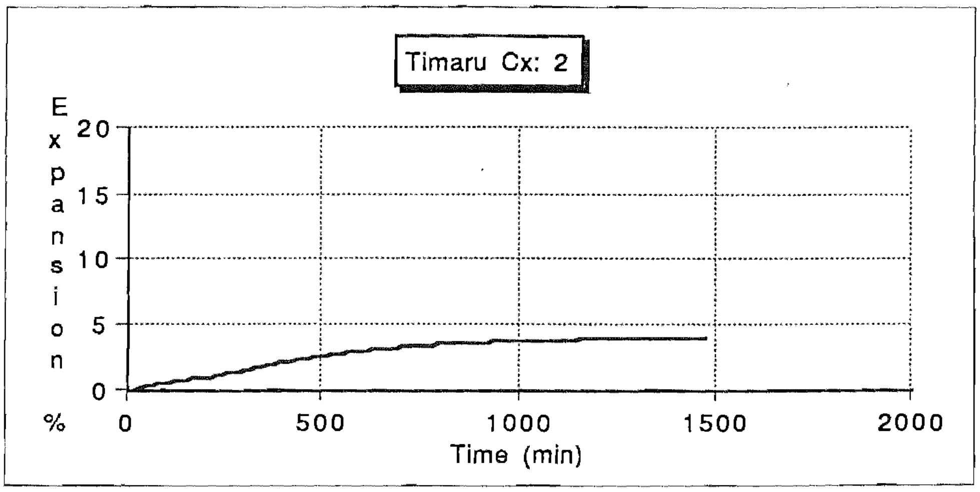


Figure H.5: Uniaxial expansion results. Site, horizon and test number given in the title of each graph.





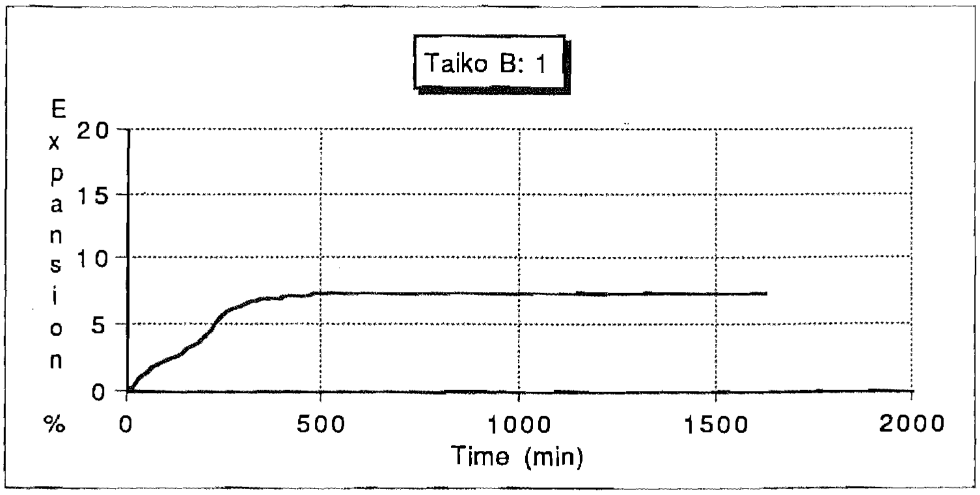
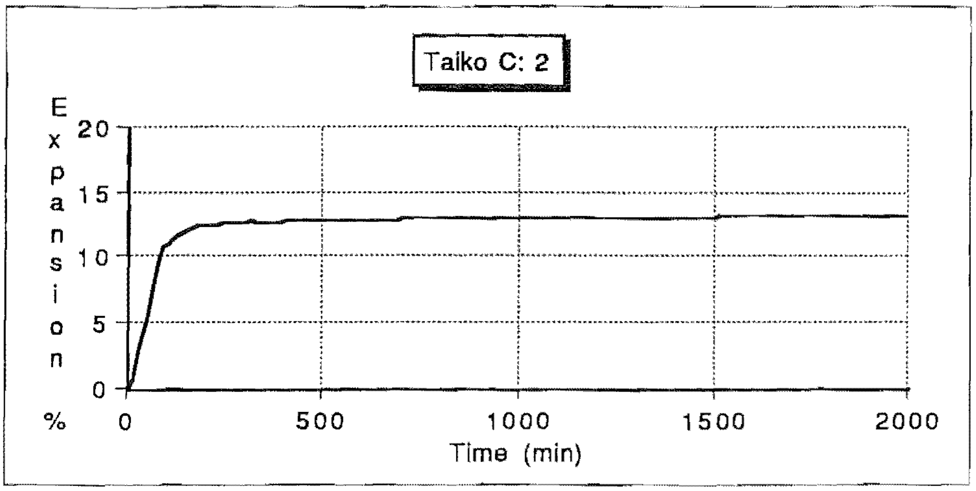
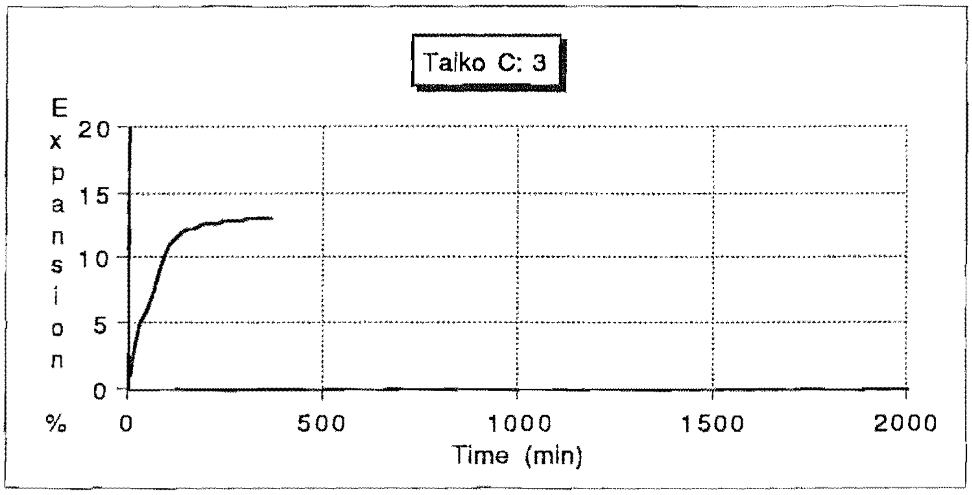


Figure H.6: Uniaxial expansion results. Site, horizon and test number given in the title of each graph.





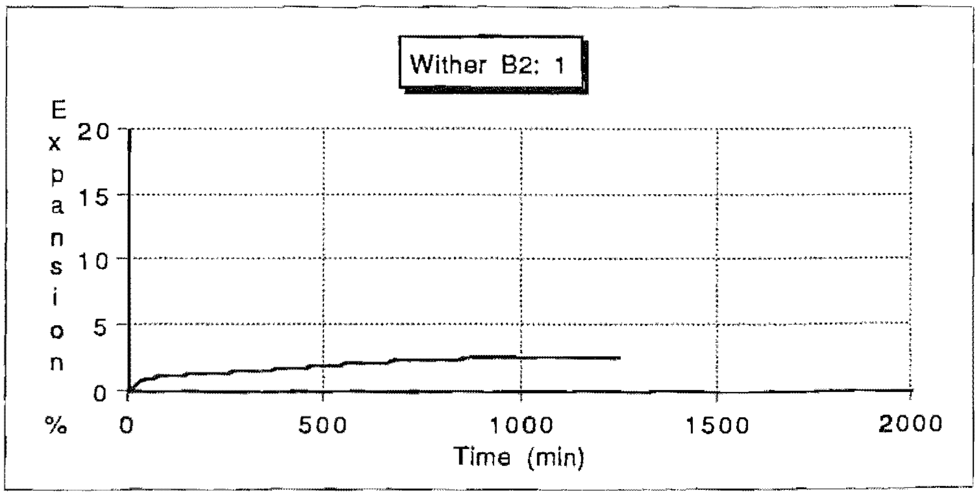
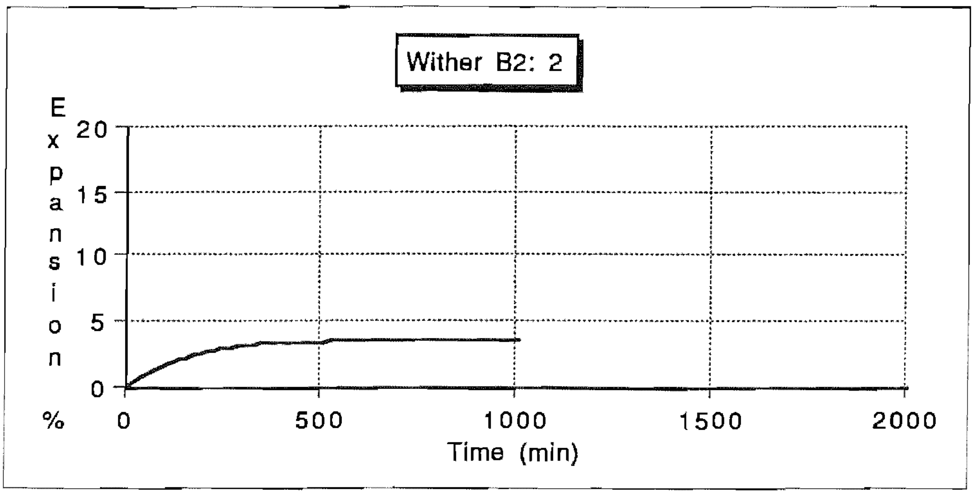
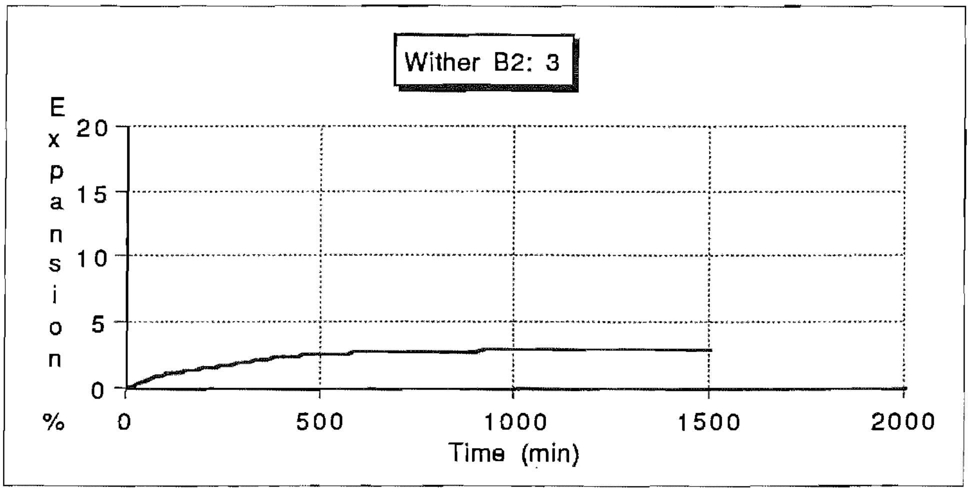


Figure H.7: Uniaxial expansion results. Site, horizon and test number given in the title of each graph.





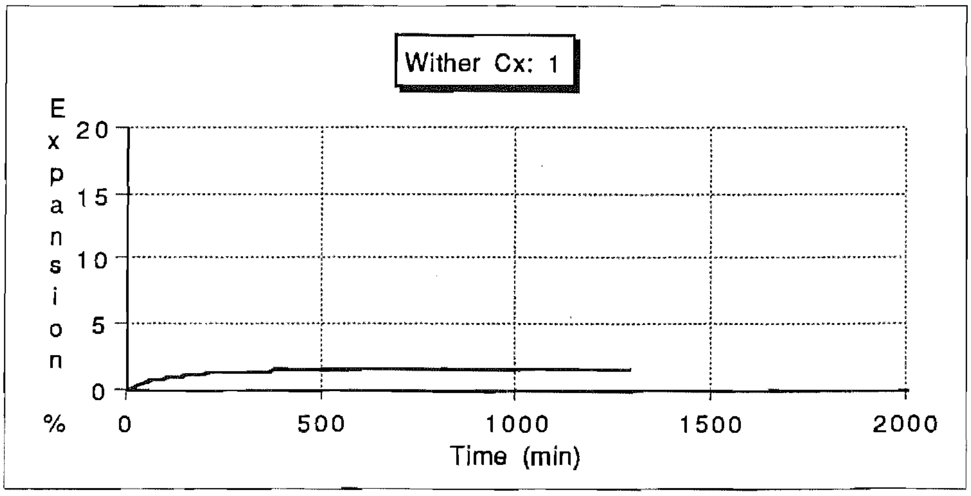
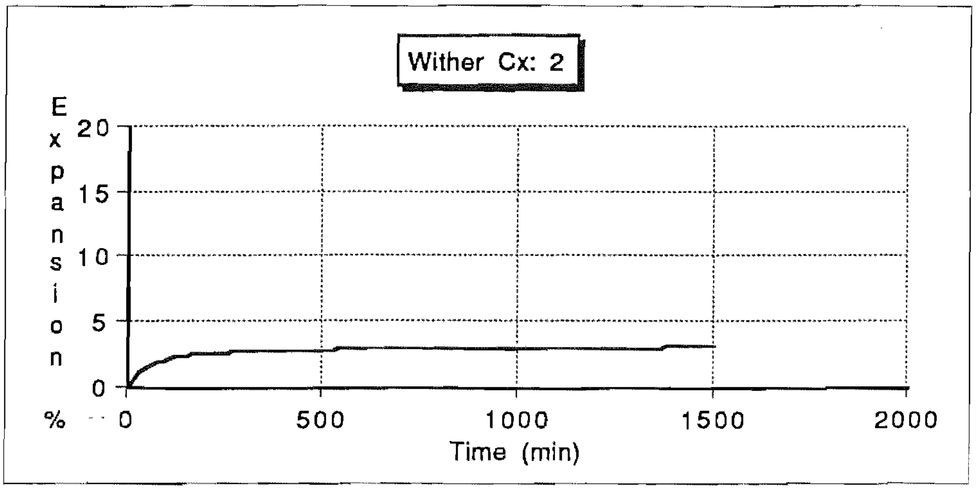
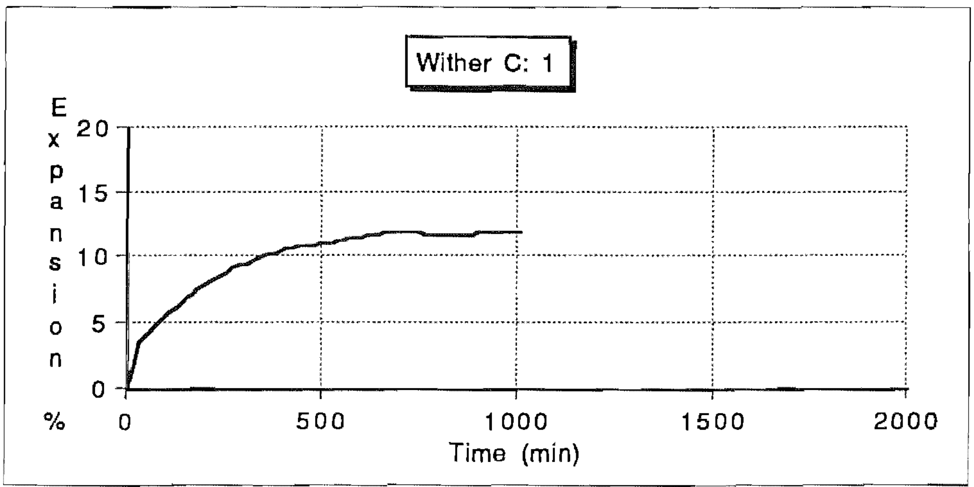


Figure H.8: Uniaxial expansion results. Site, horizon and test number given in the title of each graph.





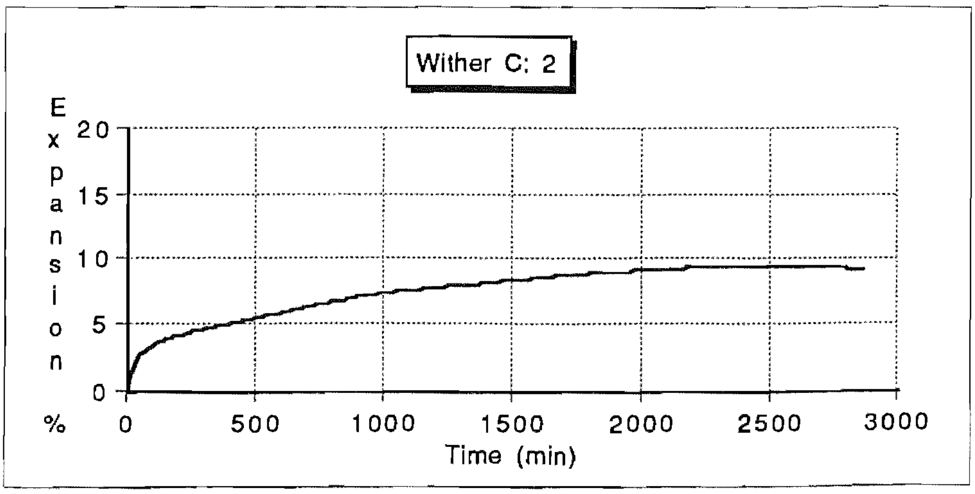
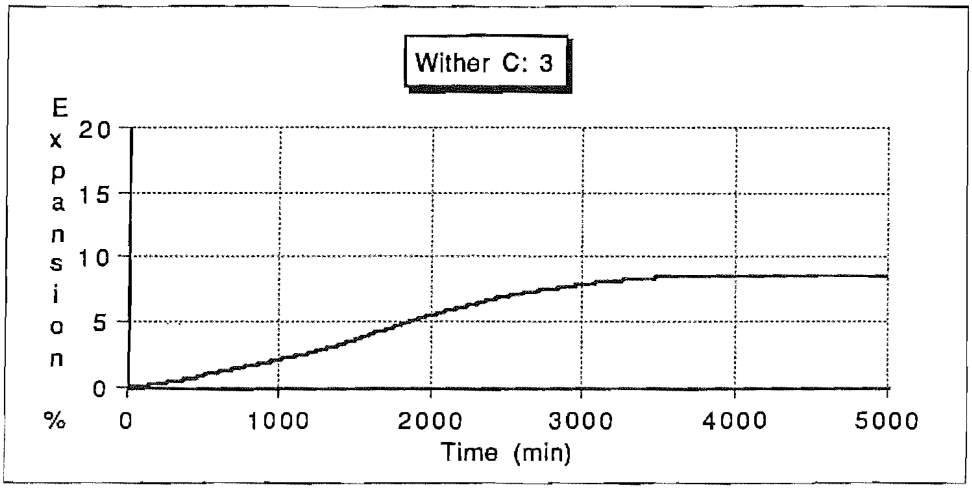
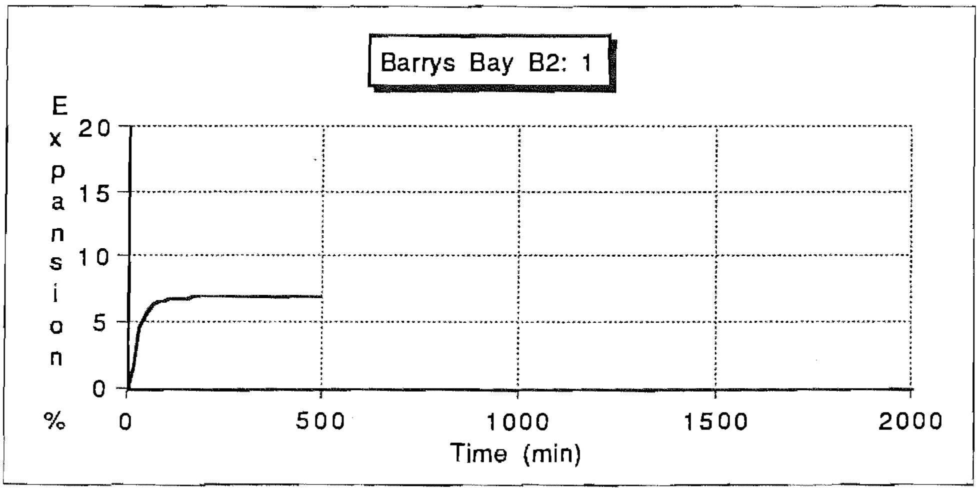


Figure H.9: Uniaxial expansion results. Site, horizon and test number given in the title of each graph.





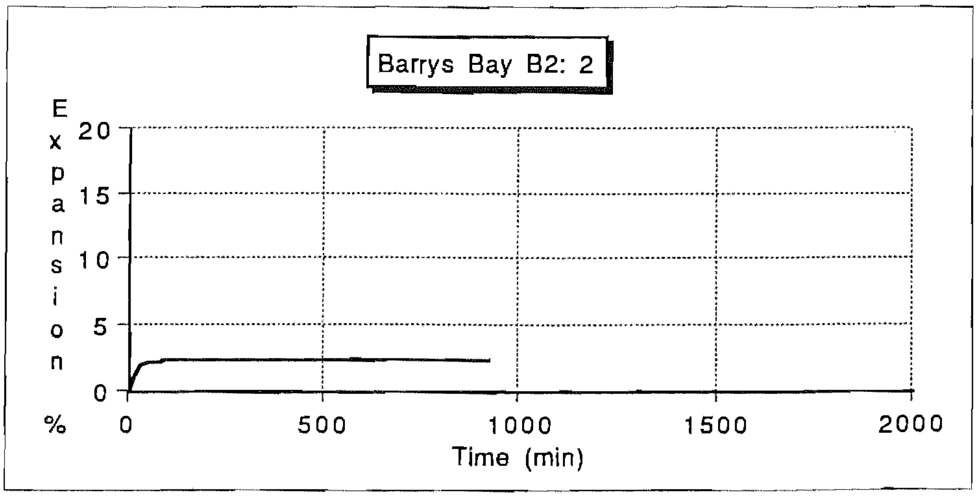
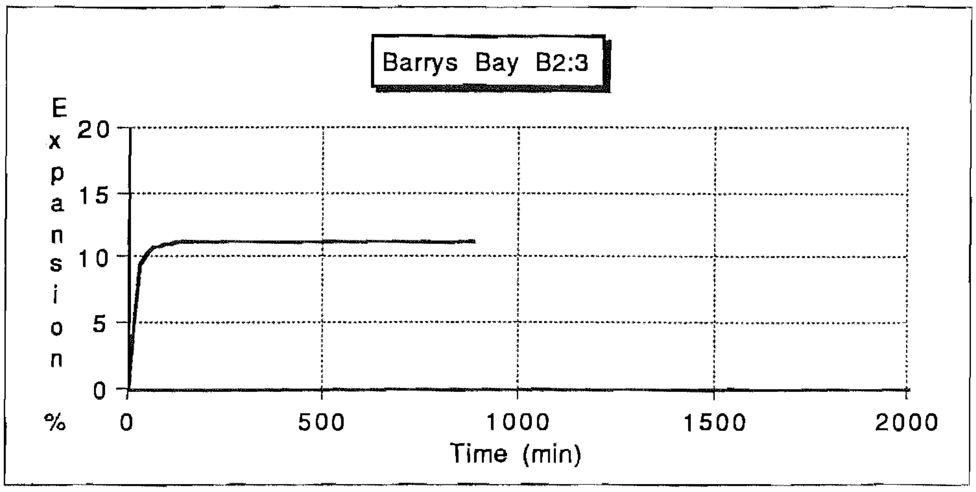
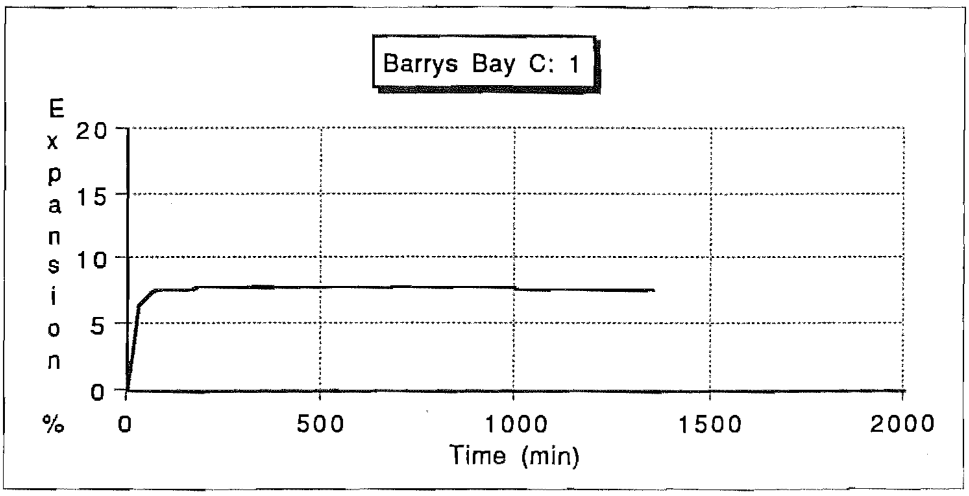


Figure H.10: Uniaxial expansion results. Site, horizon and test number given in the title of each graph.





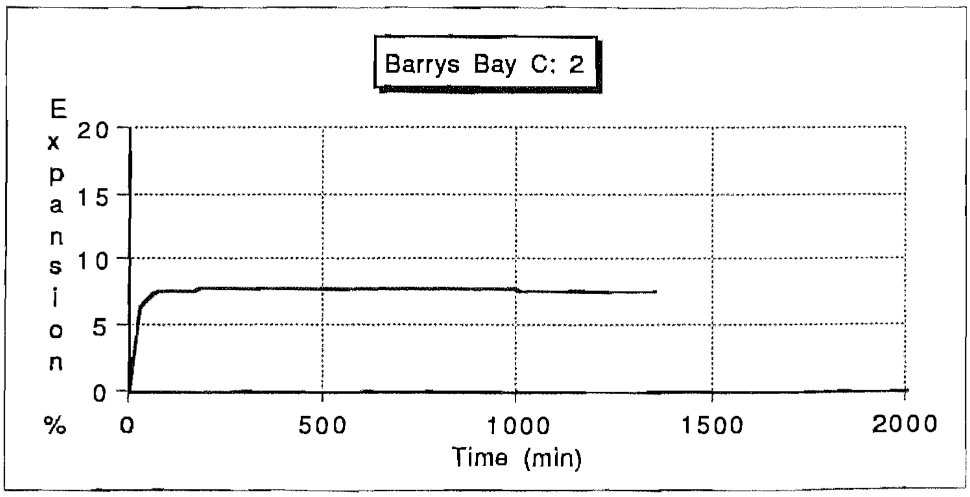


Figure H.11: Uniaxial expansion results. Site, horizon and test number given in the title of each graph.

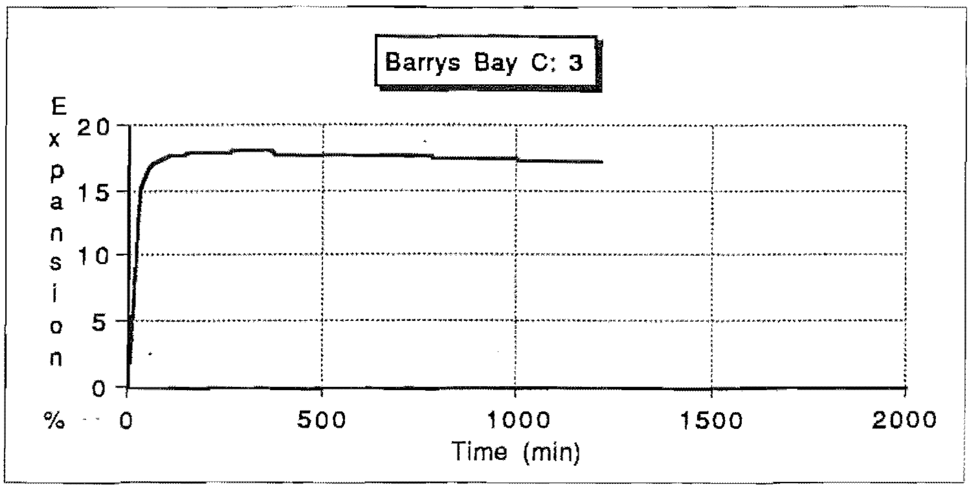


Figure H.12: Uniaxial expansion results. Site, horizon and test number given in the title of graph.

Appendix I: Atterberg Limits

NZS 4402: 1986 Test 2.2 and 2.3.

Depending on water content a soil may either be in a solid, plastic or liquid state. The plastic and Liquid limits are the water contents at which a soil passes from a solid to a plastic state, and a plastic to a liquid state respectively. As well as the plastic and liquid limits, the following related parameters were also determined:

1) Plasticity Index: The plasticity index (PI) indicates the water content range through which a cohesive soil has the properties of a plastic material.

$$PI = LL - PL$$

where: LL = the liquid Limit, and PL = the plastic limit.

2) Activity

Both the type and amount of clay influence a soils Atterberg limits. To separate the influence of both factors, the ratio of the plasticity index to the clay fraction, termed the activity of a soil can be used. Activity expresses the degree of plasticity of the clay size fraction. High activity clay minerals are highly plastic, low activity clay minerals have low plasticities. Activity can also be used to determine swell potential: soils with high activities tend to be prone to swelling.

$$\text{Activity} = PI \div \%\ \text{Clay}$$

Appendix J: Strength Tests

J.1 Direct Shear Test

J.1.1 Apparatus

1)Wykeham and Farrance 25300 direct shear box. Proving ring No. 14162: Capacity = 5 KN. Dial gauge division = 0.002 mm. 141 Div = 0.5 KN therefore 1 Div = 3.5461 N.

2) Transducer used to measure proving ring deflection.

3) A computer capable of recording results.

4) Data collection software. In this project "Picolog" was used.

J.1.2 Method

All direct shear box tests were carried out on saturated, consolidated samples. Most of the tests were drained, a few were carried out in the undrained condition. For the description of the method used see Chandler and Rodgers (1980). A description of the procedure used is given below:

1) Samples were cured at the optimum water content (OWC).

2) Samples were then compacted into a standard proctor mould, extruded and left to cure in the fog room at the Civil Engineering department at the University of Canterbury. The fog room is kept at a constant temperature of 20° and a humidity of 100%.

3) The proctor mould sample was pushed into the sample cutter. The saw was then used to cut the sample cutter (with the enclosed sample) away from the proctor mould sample. Trim the sample so that it is flush with the ends of the sample cutter. Use the trimmings to determine the water content (see Appendix C) of the sample prior to testing. It is important that the sample used for testing does not contain any of the planes of weaknesses that exist between the three layers of soil in the proctor mould. The bottom layer of the soil in the proctor mould is compacted the most, while the top layer is subjected to the least compaction. To keep the densities of the samples relatively consistent, samples were only taken out of the bottom, and middle two layers of the proctor sample. The sample cutter plus sample was then weighed to determine the dry density of the sample (for the calculation see J.1.4).

4) The shear box was prepared according to the method of Chandler and Rodgers (1980). Using the wooden extraction tool, the sample was pushed from the sample cutter

into the shear box. The two connecting screws were inserted to hold the top and bottom of the box together.

5) The shear box was placed into the shear box machine carriage. The two connecting screws were removed and the separating screws were inserted (used to separate the top and bottom of the box). The carriage was filled with distilled water and the sample was left to soak for at least 24 hours.

6) The two separating screws were taken out and the box was allowed to close. The weights used to create the normal forces were then applied via the loading arm. Typically the normal forces used were: 50, 100 and 150 KPa. Complete consolidation usually took about three hours.

7) The Samples were tested at a constant shearing rate of 0.0032 mm/min for drained tests, and 0.012 mm/min for undrained tests. The transducer measures the force required to maintain the top of the shear box in the same position while the shear box carriage is moved at a constant rate. The computer records the transducer data with a sampling period of 10 minutes. From this data, a force/stress versus time graph may be constructed. Failure usually occurred after approximately 1 day for drained tests and six hours for undrained tests.

8) Save the test data to disk and print off a graph of the normal stress against displacement.

J.1.3 Calculations

1) Normal Stress

For drained tests, the vertical effective stress (σ'_v) is calulated using the following formula:

$$\sigma'_v = (\rho - \rho_w)g.z$$

where: ρ = Bulk density (kg/m^3); ρ_w = Density of water = 1000 kg/m^3; g = 9.8 m/s^2; z = over burden depth (m).

For undrained tests the following formula is used:

$$\sigma_v = \rho.g.z$$

2) Shear Stress

For both drained and undrained tests, the following formula was used to convert force to shear strength (τ) in kPa:

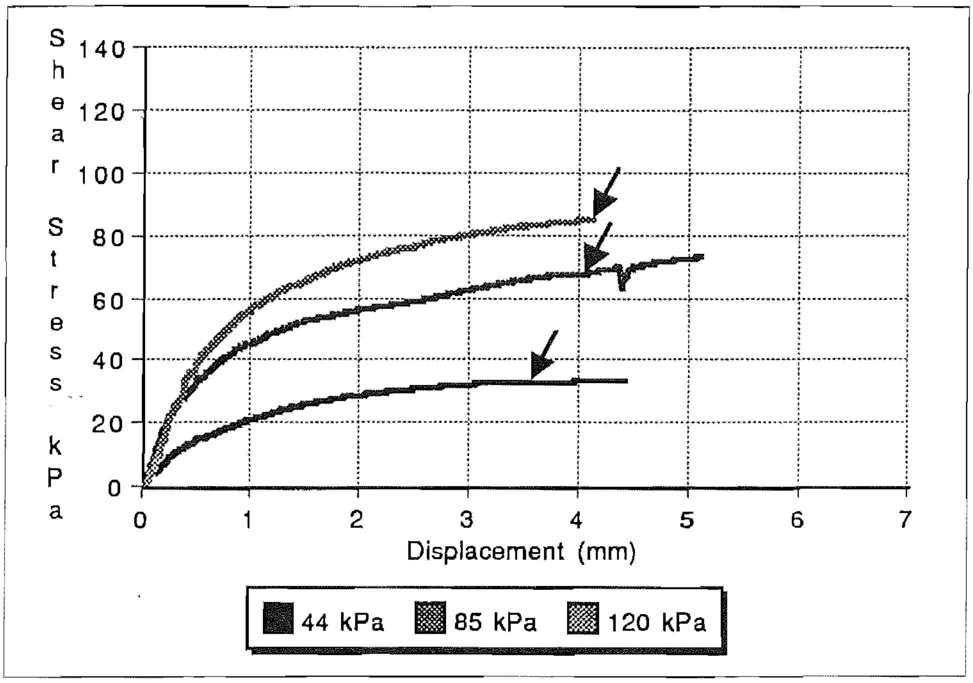
$$\tau = F \div A$$

where: F = force (in N); A = cross sectional area of sample = 7.7475×10^{3} m^2 (sample radius = 4.966 mm, therefore, area = $\pi \times r^2 = 7.7475 \times 10^{-3}$ m^2).

J.1.4 Results

Figures J.1-4 are the shear strength/displacement curves for all of the tests that were carried out. Figures J.5-10 are the normal stress against shear stress graphs for all of the tests that were carried out.

(a)



(b)

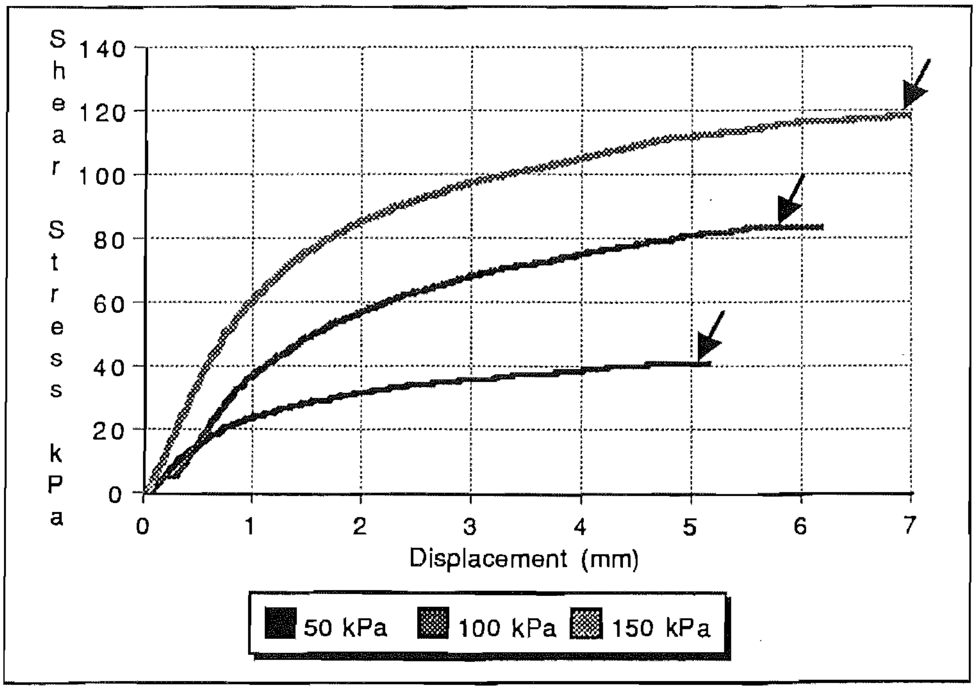
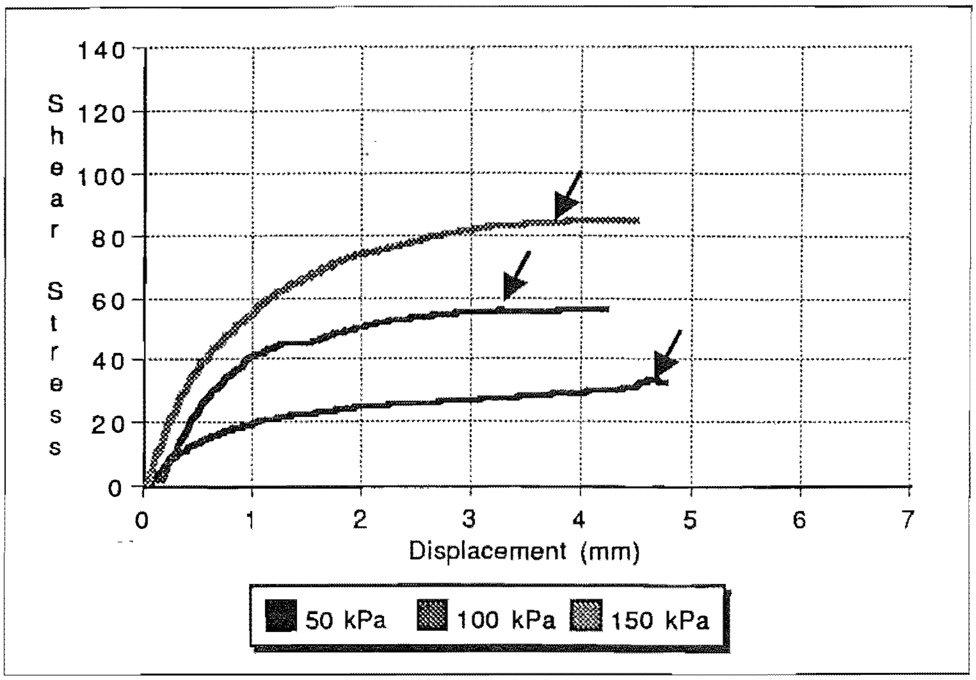


Figure J.1 Stress/displacement graphs from drained direct shear box testing on loess from (a) Ahuriri quarry and the Gebbies pass site (b). Normal pressures are given in the legend. Arrows indicate the estimated point of failure.

(a)



(b)

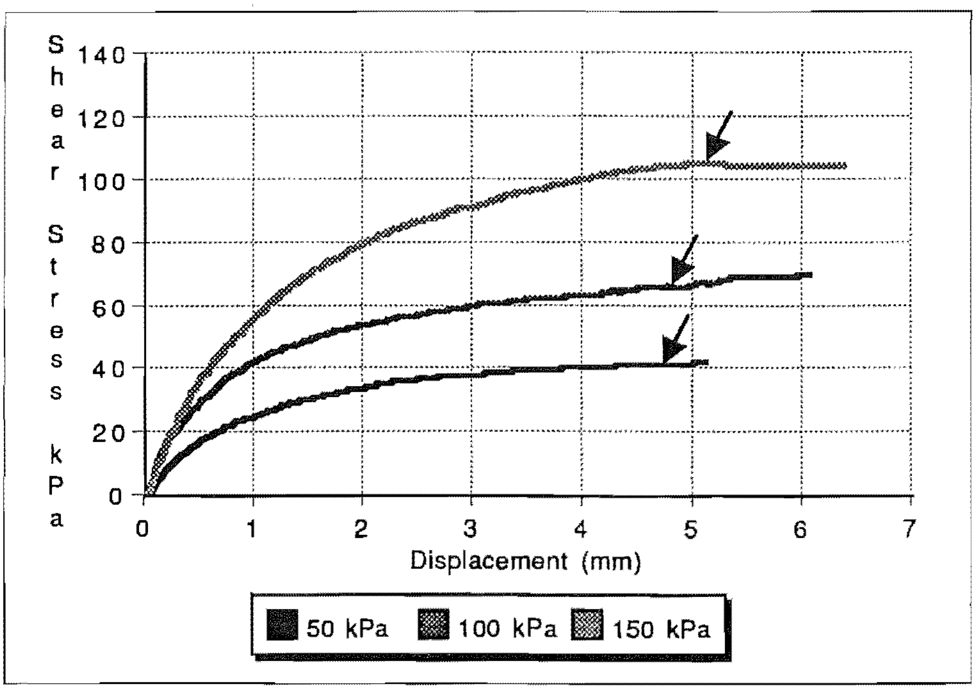
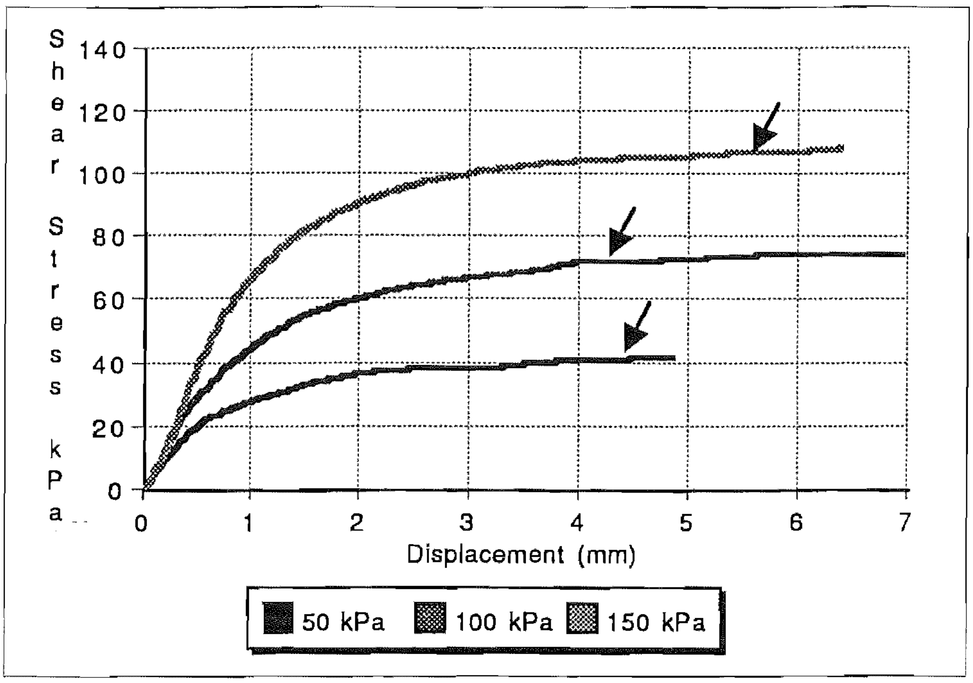


Figure J.2 Stress/displacement graphs from drained direct shear box testing on loess from the (a) Timaru and (b) Taiko sites. Normal pressures are given in the legend. Arrows indicate estimated point of failure.

(a)



(b)

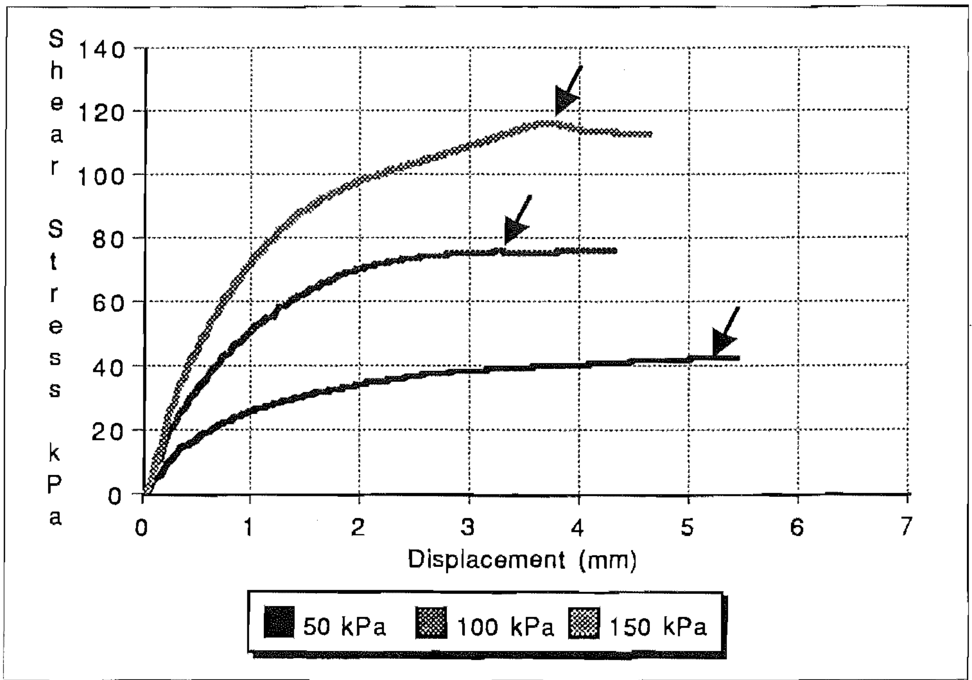
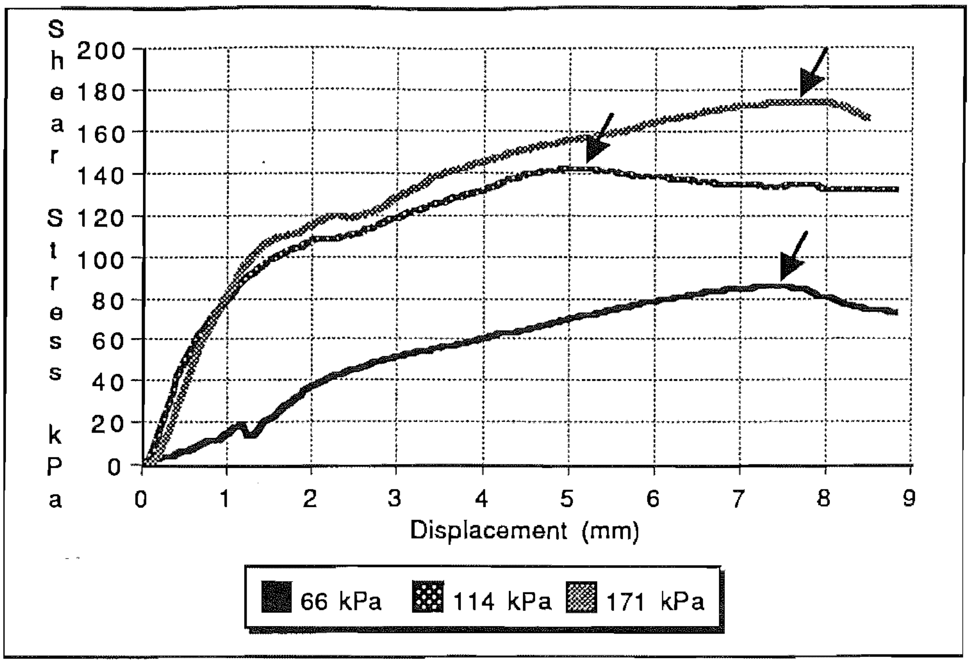


Figure J.3 Stress/displacement graphs from drained direct shear box testing on loess from the (a) Wither Hills and (b) Barrys bay sites. Normal pressures are given in the legend. Arrows indicate the estimated point of failure.



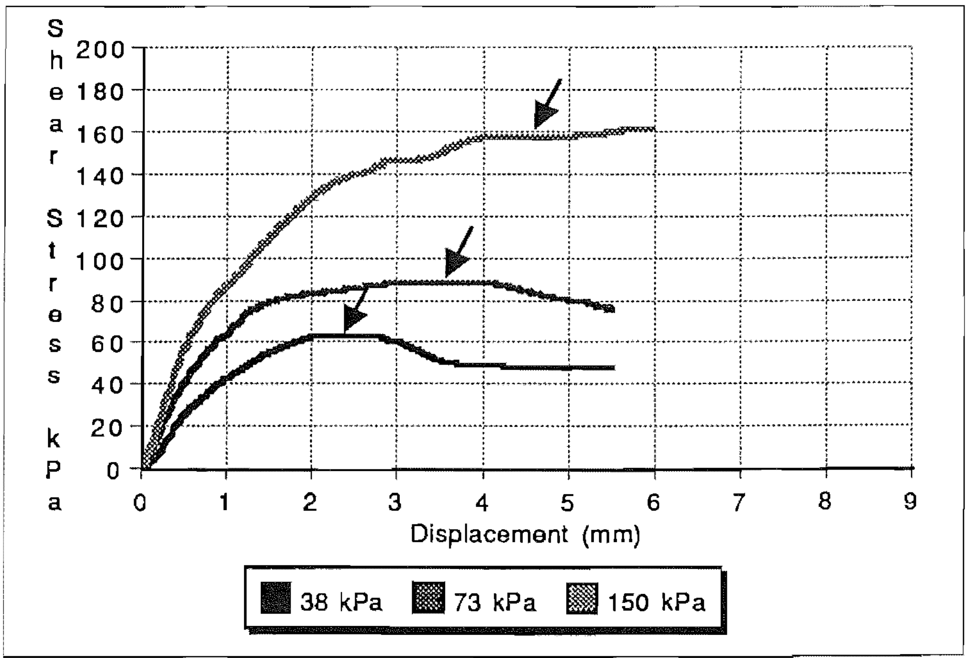


Figure J.4 Stress/displacement graphs from direct shear box testing on loess from Ahuriri quarry treated with 2.5% quicklime; (a) = undrained test, (b) = drained test. Arrows indicate estimated point of failure.

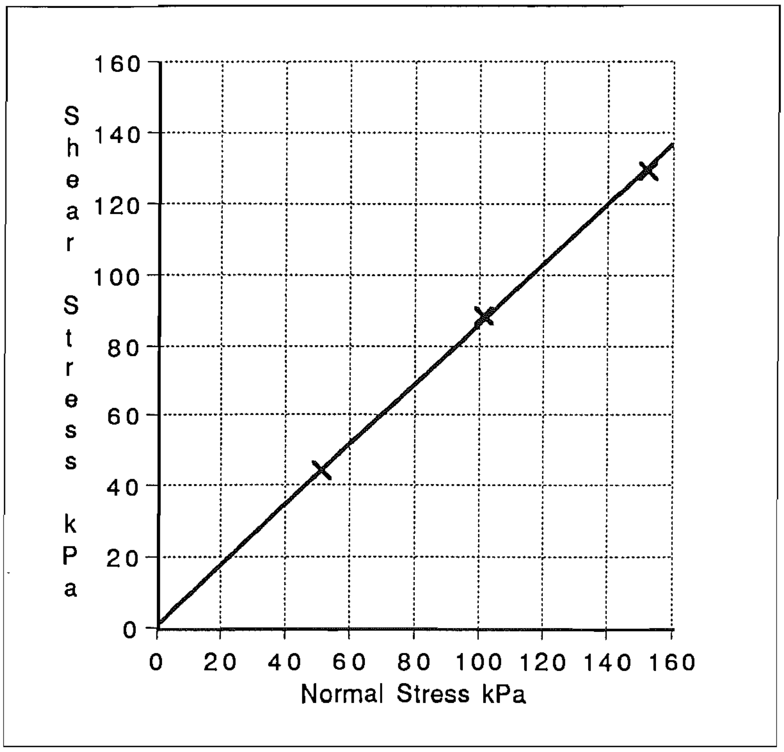


Figure J.5: Shear strength characteristics of loess from the Gebbies Valley site.

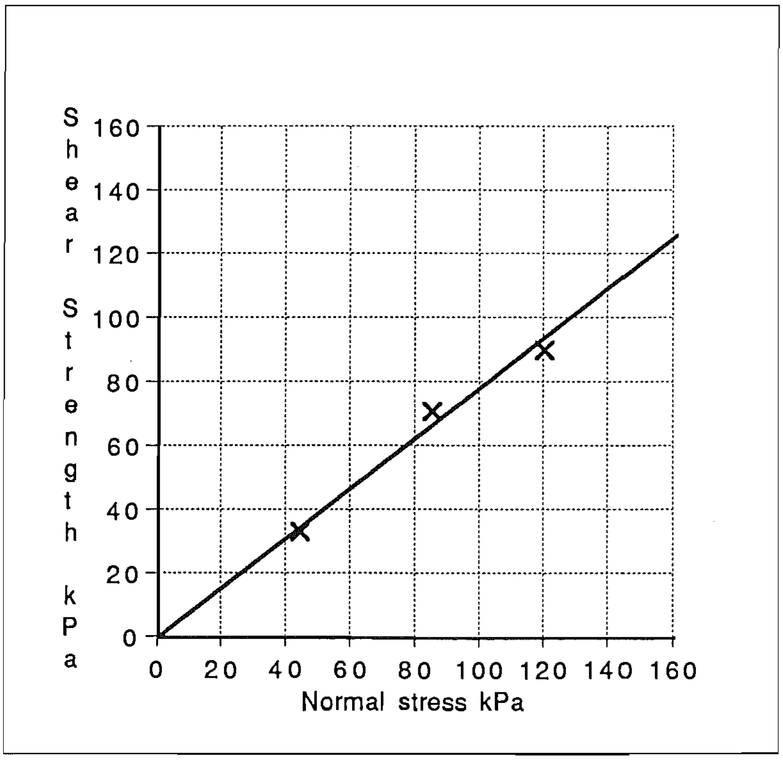


Figure J.6: Shear strength characteristics of loess from the Gebbies Valley site.

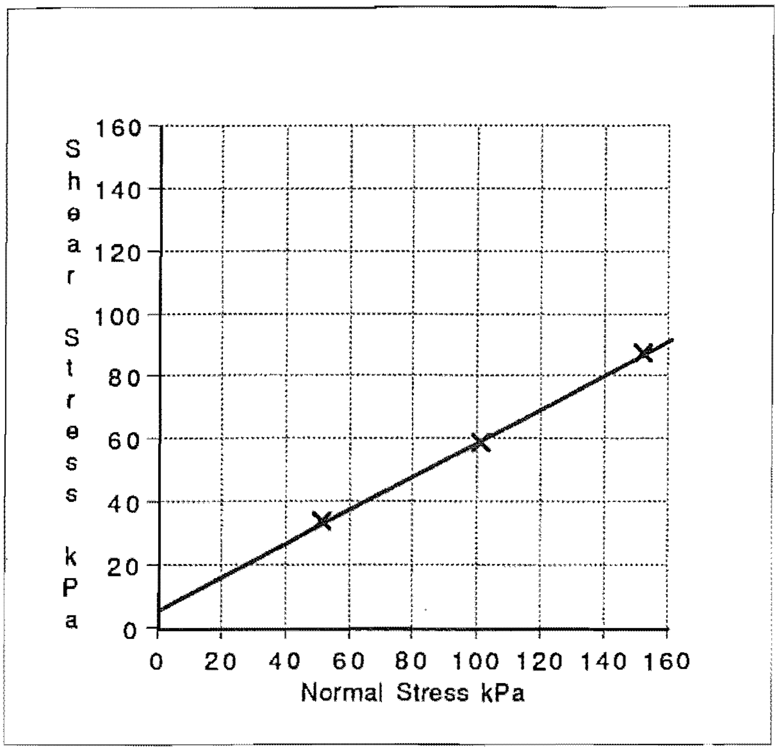


Figure J.7: Shear strength characteristics of loess from the Timaru Downs site.

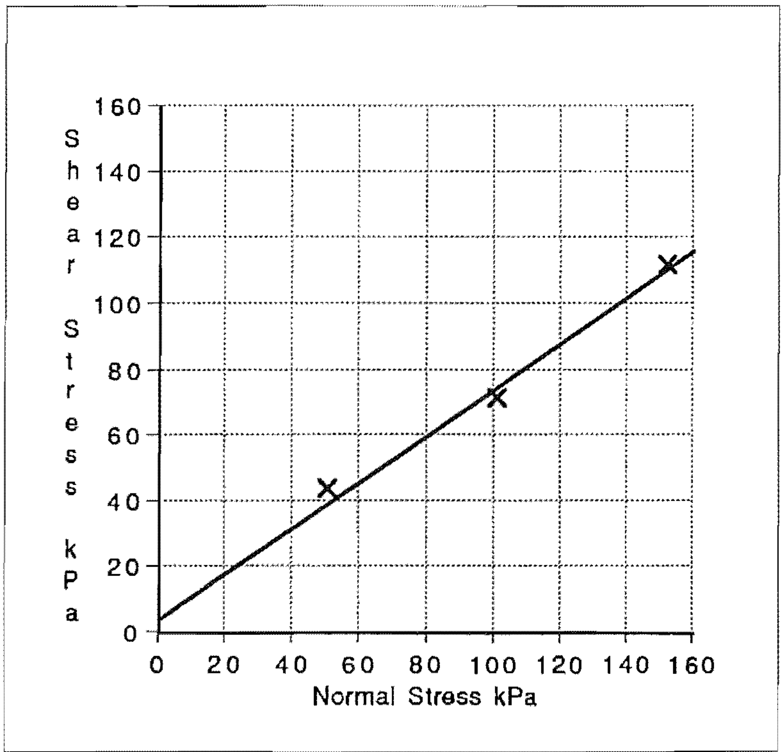


Figure J.8: Shear strength characteristics of loess from the Taiko site.

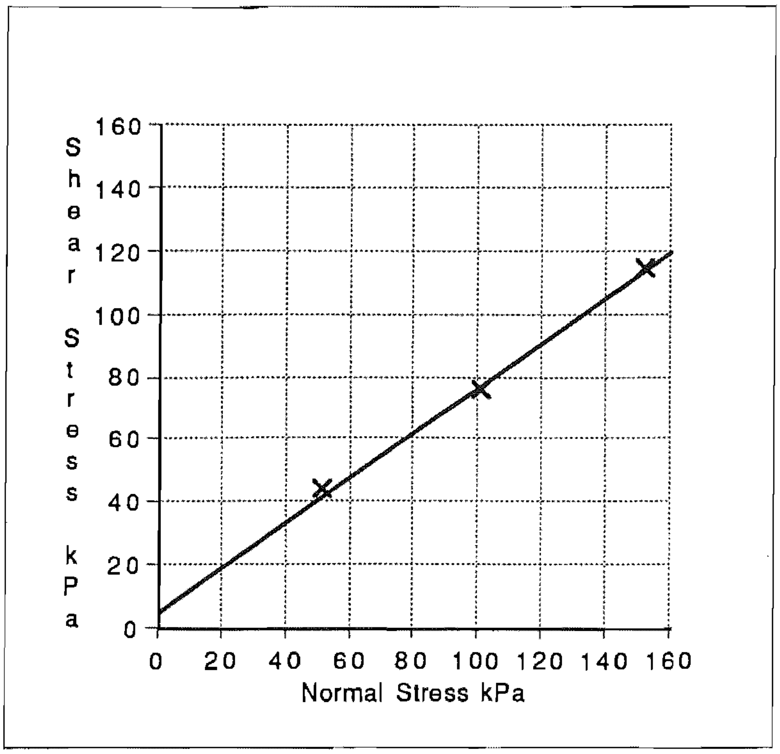


Figure J.9: Shear strength characteristics of loess from the Wither Hills site.

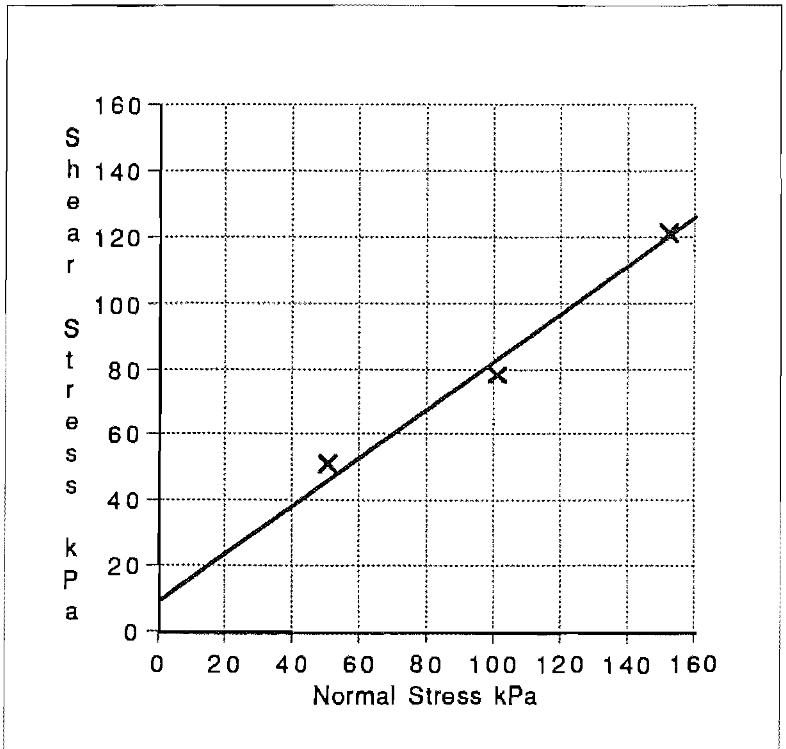


Figure J.10: Shear strength characteristics of loess from the Barrys Bay site.

J.2 Unconfined Compressive Strength Test

Method based on: NZS 4402: 1986 Test 6.3.1

J.2.1 Apparatus

Wykeham Farrance 10 000 kg stepless loading frame. Proving ring No. 1105: Capacity = 100 KN. Dial gauge division = 0.002 mm. 131 Div = 10 000 N, therefore: 1 Div = 76.335878 N.

J.2.2 Method

1) Samples were compacted into a proctor mould (length = 115.5 mm, diameter = 105 mm) and cured in the fog room (99% humidity and a temperature of 20°).

2) The moulds were loaded at a rate of approximately 0.85 mm/min (0.0142 mm/second). For some reason the compression rate on the machine was not able to be adjusted. The compression rate which was used was the rate at which the machine "happened" to be doing at the time of testing. The ideal compression rate would have been 0.5 mm/min.

3) The increase of axial stress (KPa) with time is recorded until failure occurs.

4) After the test, the compression rate for the test was calculated by dividing compression by time. The compression rate for each test was very similar. The average compression rate: 0.0142, was used in the calculations below.

J.2.3 Calculations

Table J.1 is an example of the spread sheet used to calculate the Unconfined compressive strength (UCS) of the samples. The calculations used to derive the UCS values are listed below:

1) Compression (C) in mm:

$$C = T \times R$$

Where: **T** = time (in seconds). **R** = average compression rate of the testing machine (= 0.0149227 mm/s).

Failure compression can be calculated by multiplying the time taken for specimen failure by the compression rate.

2) Corrected area (A) in mm^2

$$A = A_0 \div (1 - S)$$

Where: $\mathbf{A_0}$ = initial area of the specimen normal to the axis (= 8659.0148 mm^2).

S = stain = C ÷ 115.5. Strain % = S x 100.

3) Axial force (F) in N

$$F = 76.335878 \times r$$

Where: **r** = dial gauge reading.**76.335878** = The factor which converts the dial gauge reading into Newtons (see J.2.1).

4) Stress (S) in MPa

$$S = F \div A$$

Where Unconfined Compressive Strength UCS is defined as the stress at which the specimen fails.

J.2.4 Results

Results in the form of stress/strain curves are shown in Fig. J.11-18.

Sample:	1.25Q/1					
Fail Comp:	4.178356	Comp mass:	2022.5	Test mass:	1791.4	
Fail time:	280	Comp w%:	0.1585	Test w%:	2.61	
Comp rate:	0.0149227	Dry Density:	1745.79197	Strength:	0.63	MPa
		% of MDD:	99.93	Strain%:	3.62	
				Youngs M:	17.4	MPa
Time	Compression	Load gauge	Corr area	Axial force	Strain	Stress
(seconds)	(mm)	(r)	(mm2)	(N)	(%)	(MPa)
22	0.3282994	10	8687.53592	763.35878	0.284	0.088
58	0.8655166	20	8734.61433	1526.71756	0.749	0.175
105	1.5668835	30	8796.85121	2290.07634	1.357	0.26
133	1.9847191	40	8834.35186	3053.43512	1.718	0.346
160	2.387632	50	8870.81727	3816.7939	2.067	0.43
208	3.1039216	60	8936.39344	4580.15268	2.687	0.513
221	3.2979167	65	8954.32084	4961.83207	2.855	0.554
241	3.5963707	70	8982.04233	5343.51146	3.114	0.595
280	4.178356	74.75	9036.59594	5706.10688	3.618	0.631
306	4.5663462	73	9073.33467	5572.51909	3.954	0.614
370	5.521399	72.5	9165.05399	5534.35115	4.78	0.604

Table J.1: Spreadsheet used to determine Unconfined Compressive Strength.

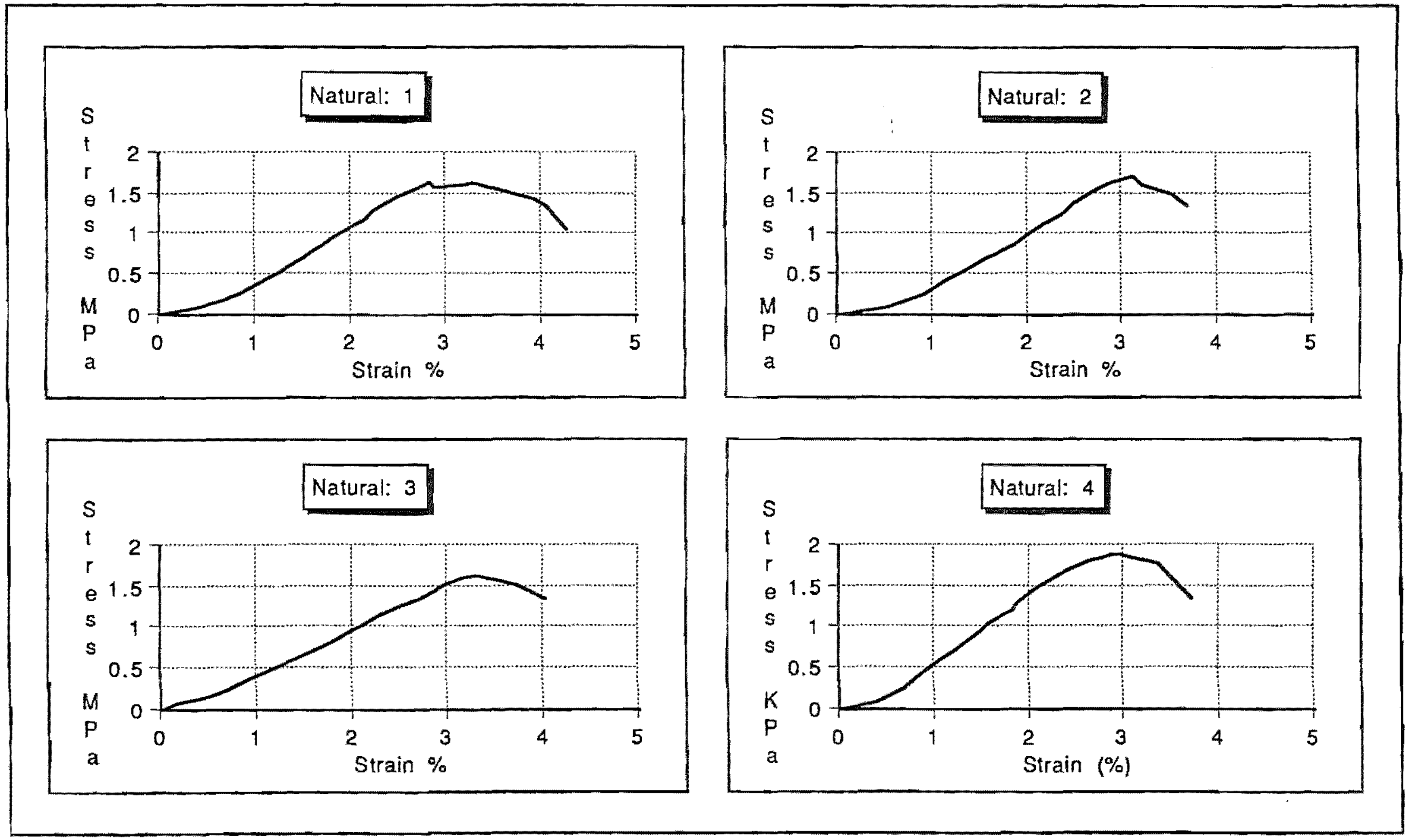


Fig J.11 Stress/Strain relationships from unconfined compressive strength tests carried out on Ahuriri loess.

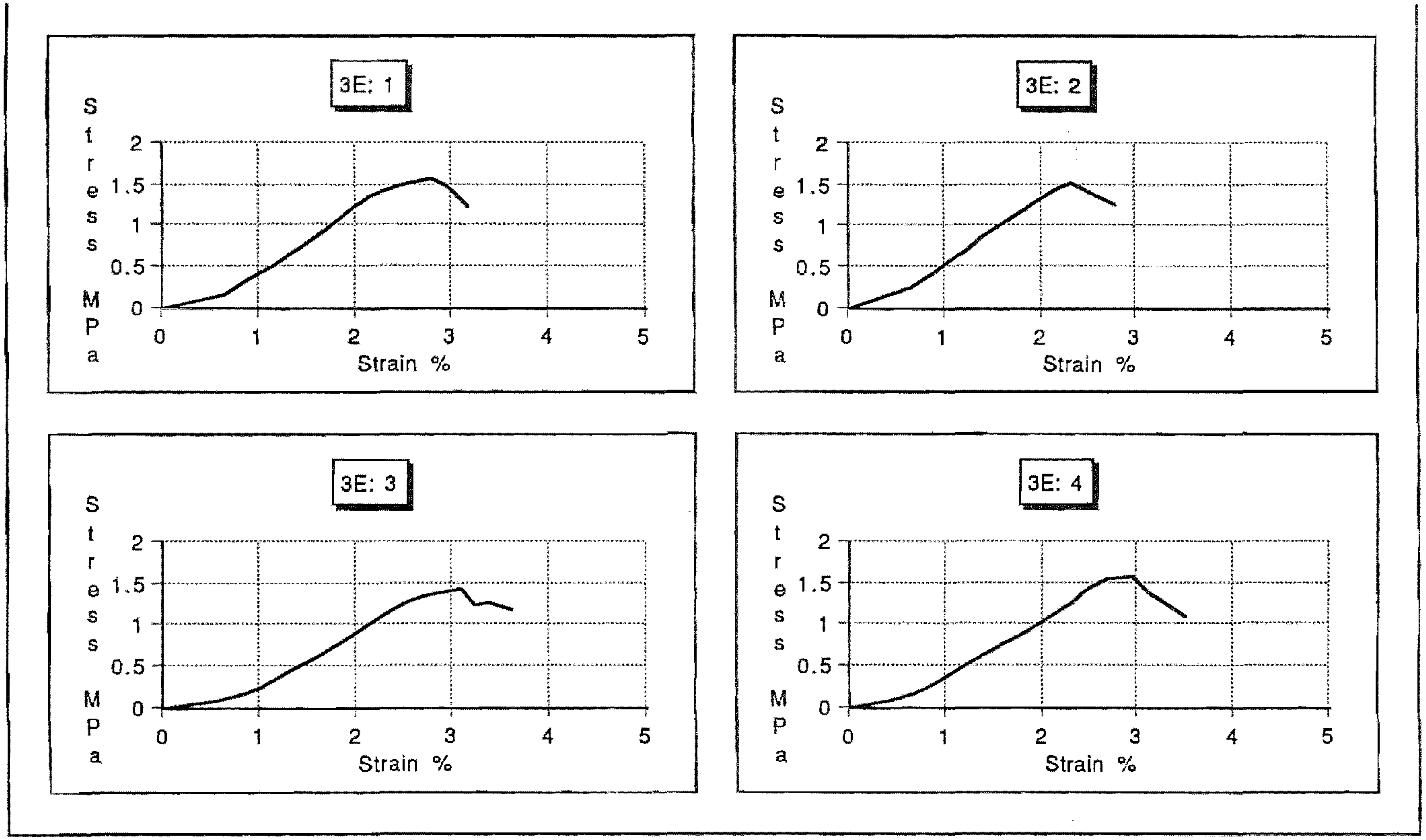


Fig J.12 Stress/Strain relationships from unconfined compressive strength tests carried out on Ahuriri loess plus Endurazyme applied at a rate of 3 litres/3.5 m^3.

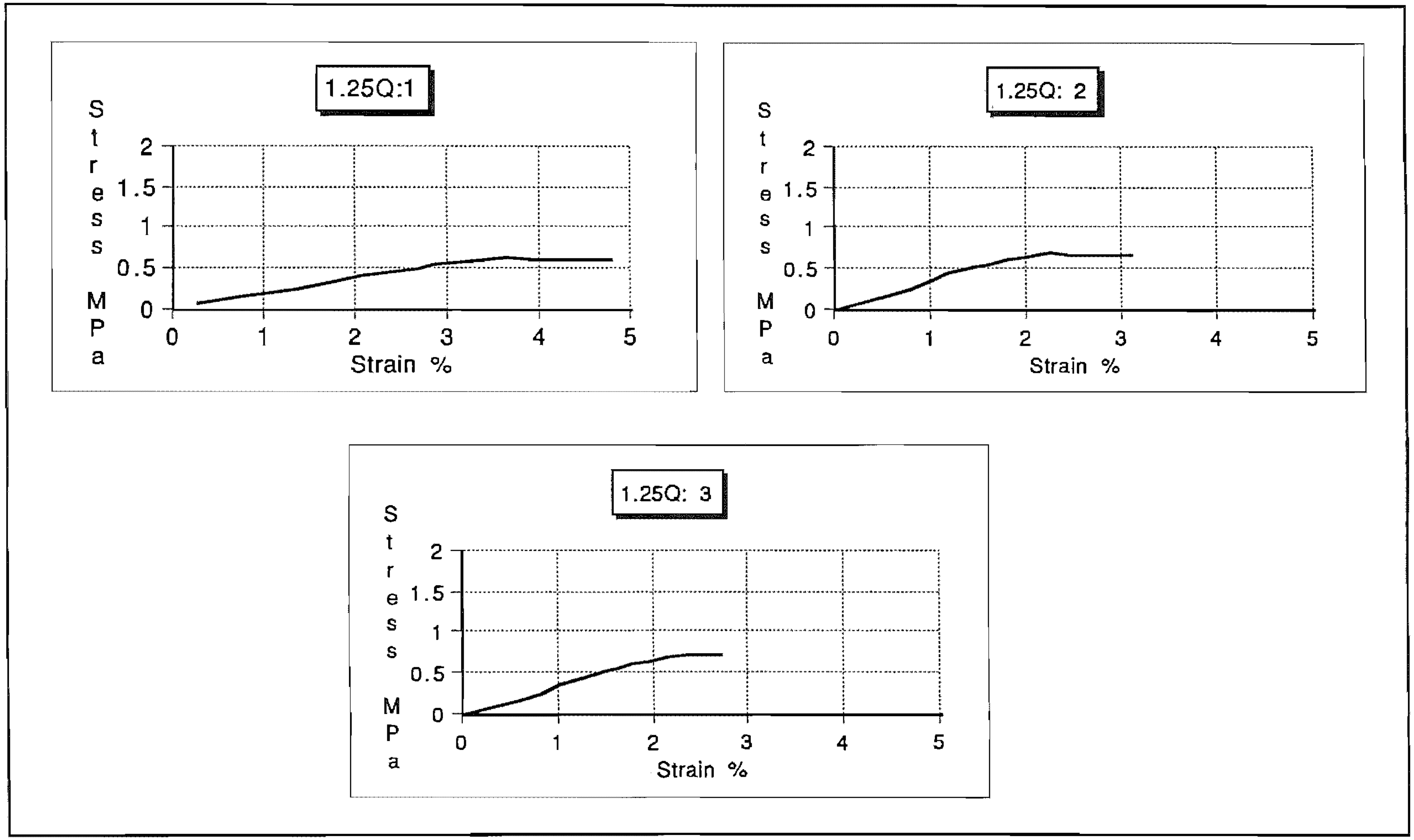


Fig J.13: Stress/Strain relationships from unconfined compressive strength tests carried out on Ahuriri loess plus 1.25% quicklime.

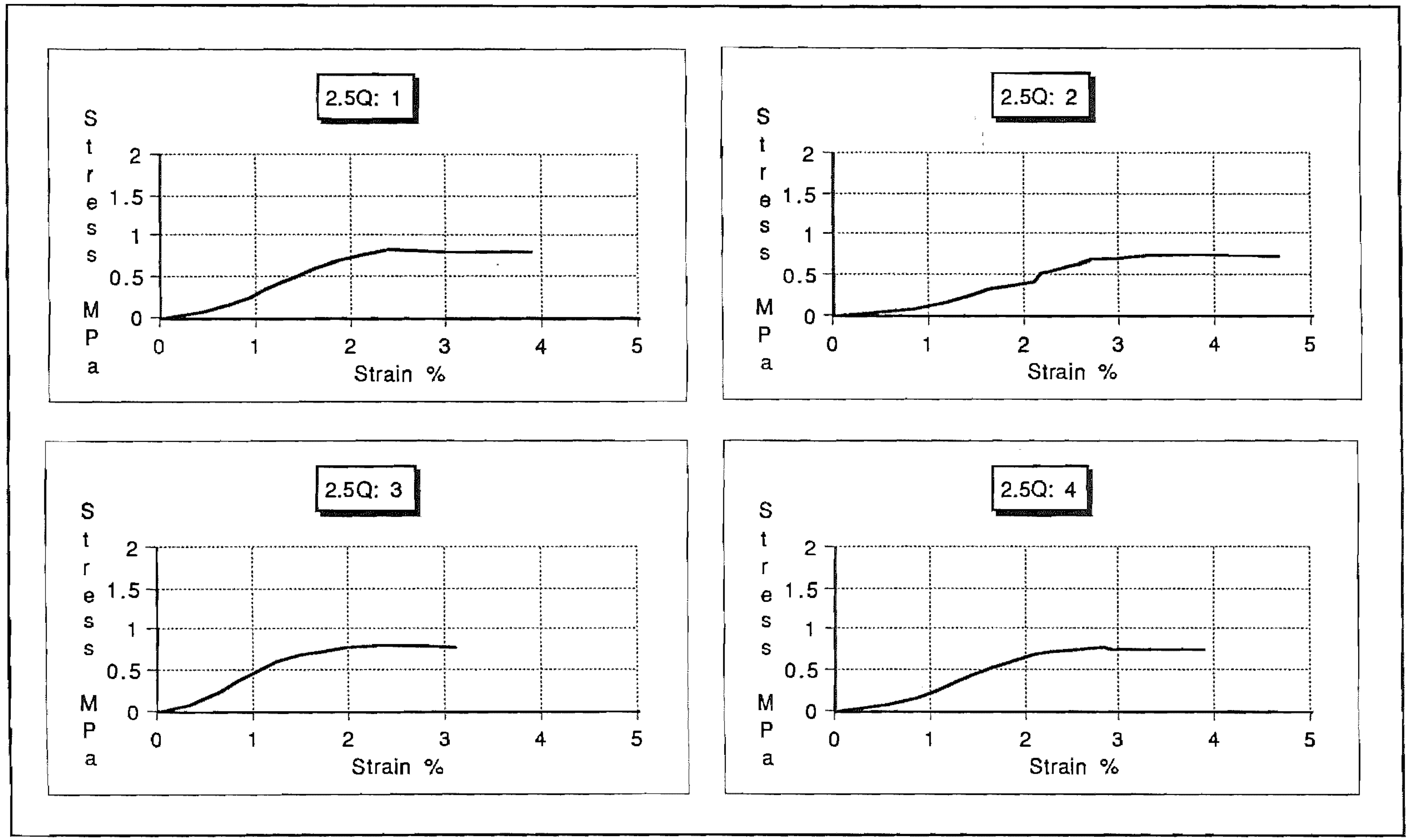


Fig J.14: Stress/Strain relationships from unconfined compressive strength tests carried out on Ahuriri loess plus 2.5% quicklime.

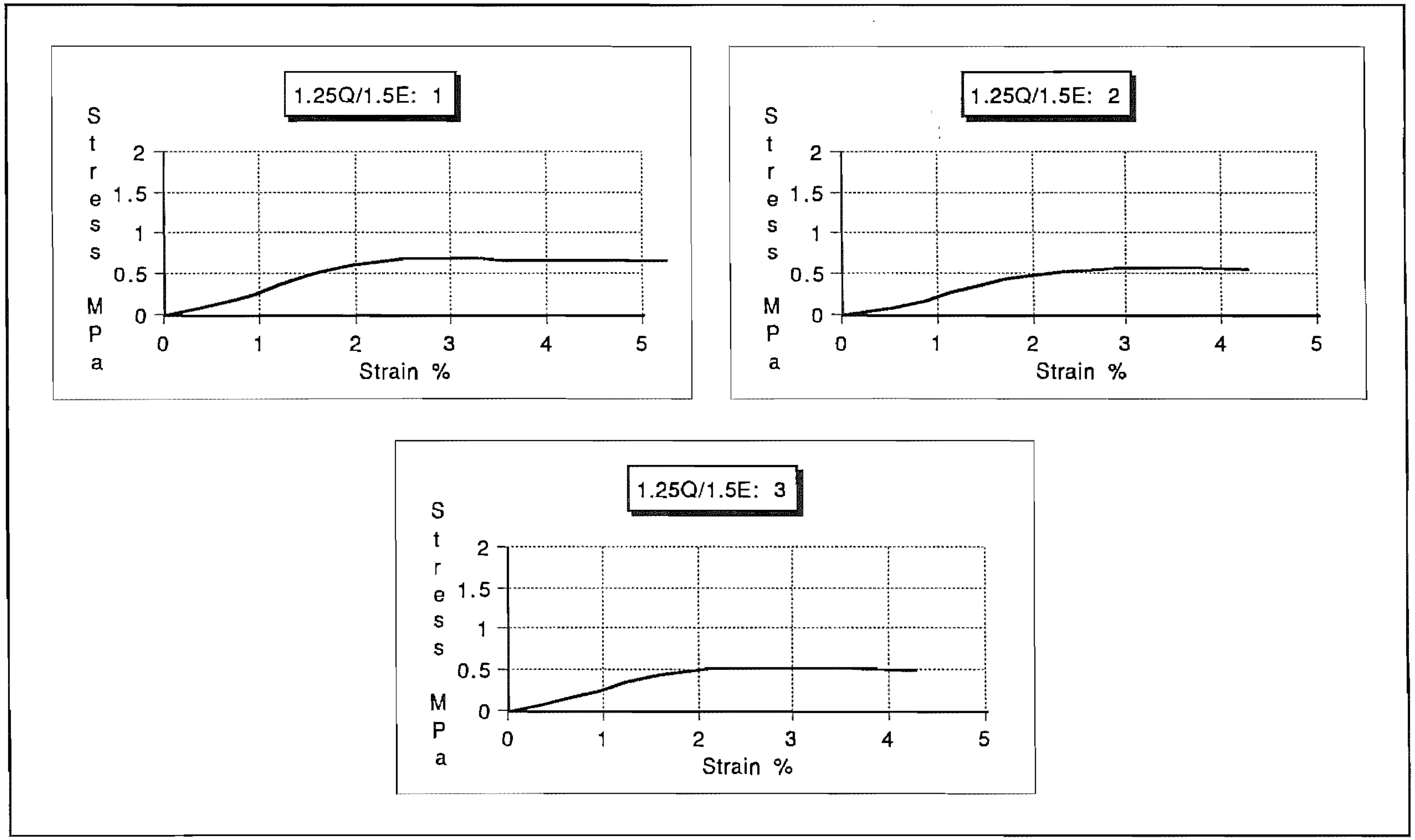


Fig J.15: Stress/Strain relationships from unconfined compressive strength tests carried out on Ahuriri loess plus 1.25% quiklime, and Endurazyme (1.5 litres /3.5 m^3.

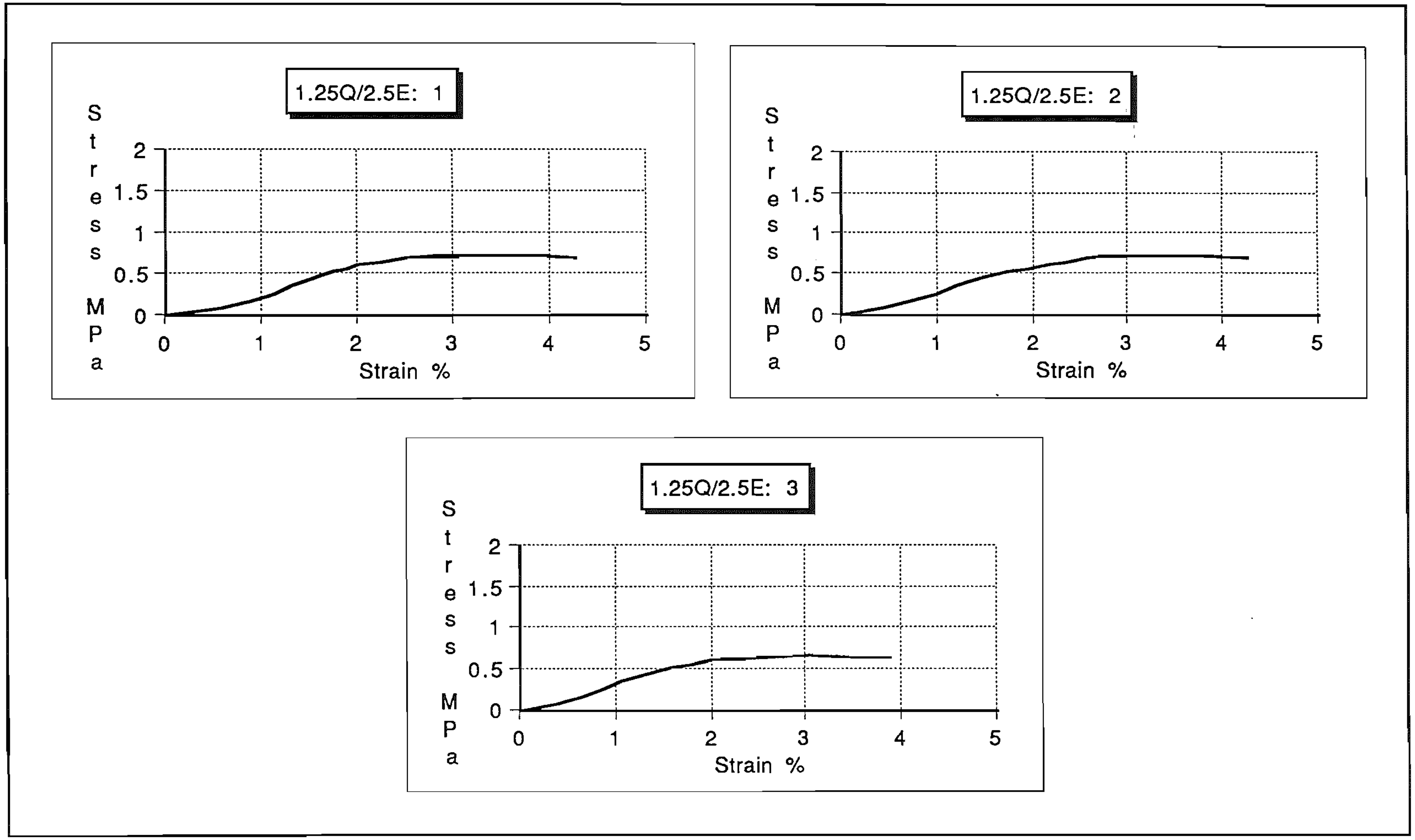


Fig J.16 Stress/Strain relationships from unconfined compressive strength tests carried out on Ahuriri loess plus 1.25% quiklime, and Endurazyme (2.5 litres/ 3.5m^3).

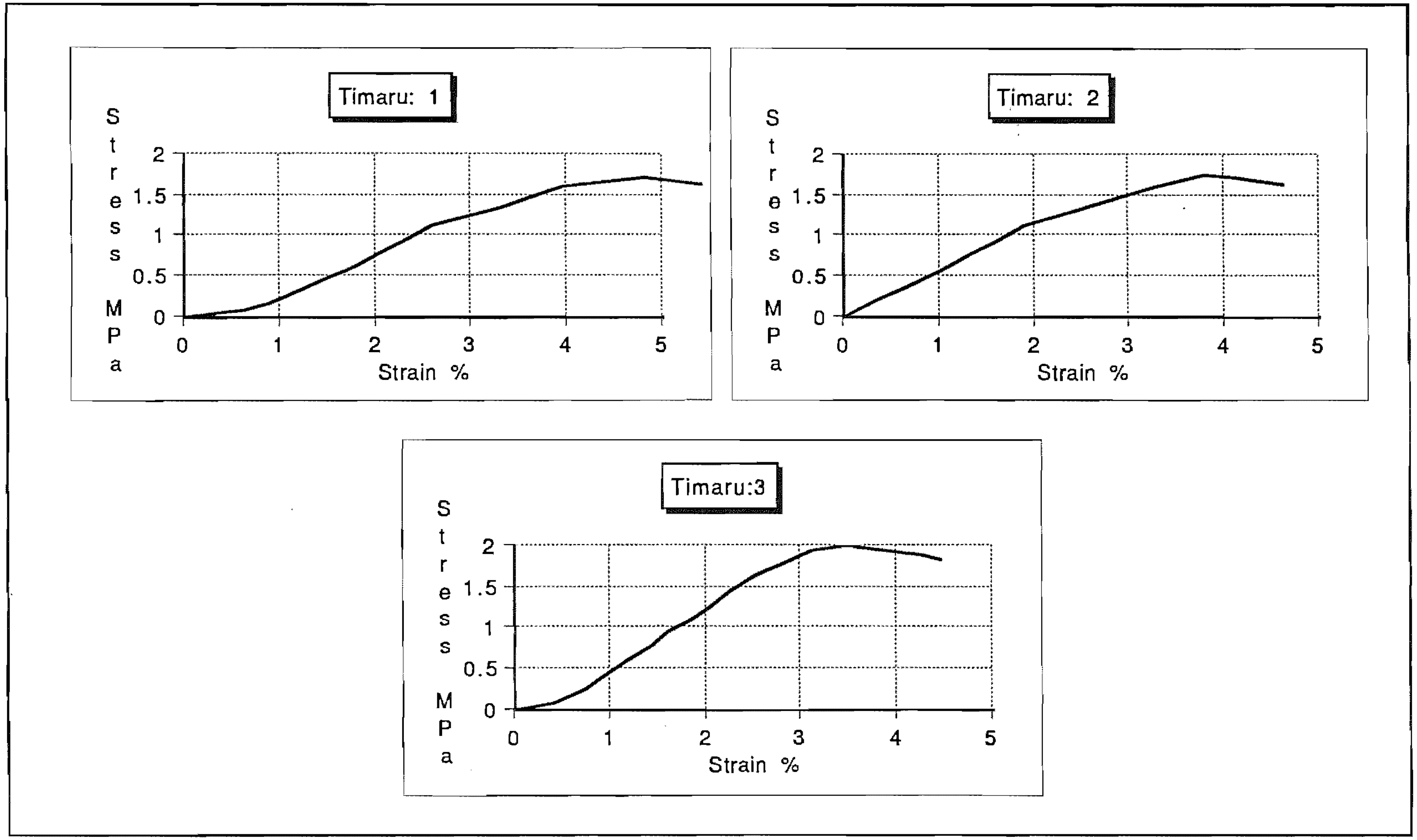


Fig J.17 Stress/Strain relationships from unconfined compressive strength tests carried out on Timaru loess.

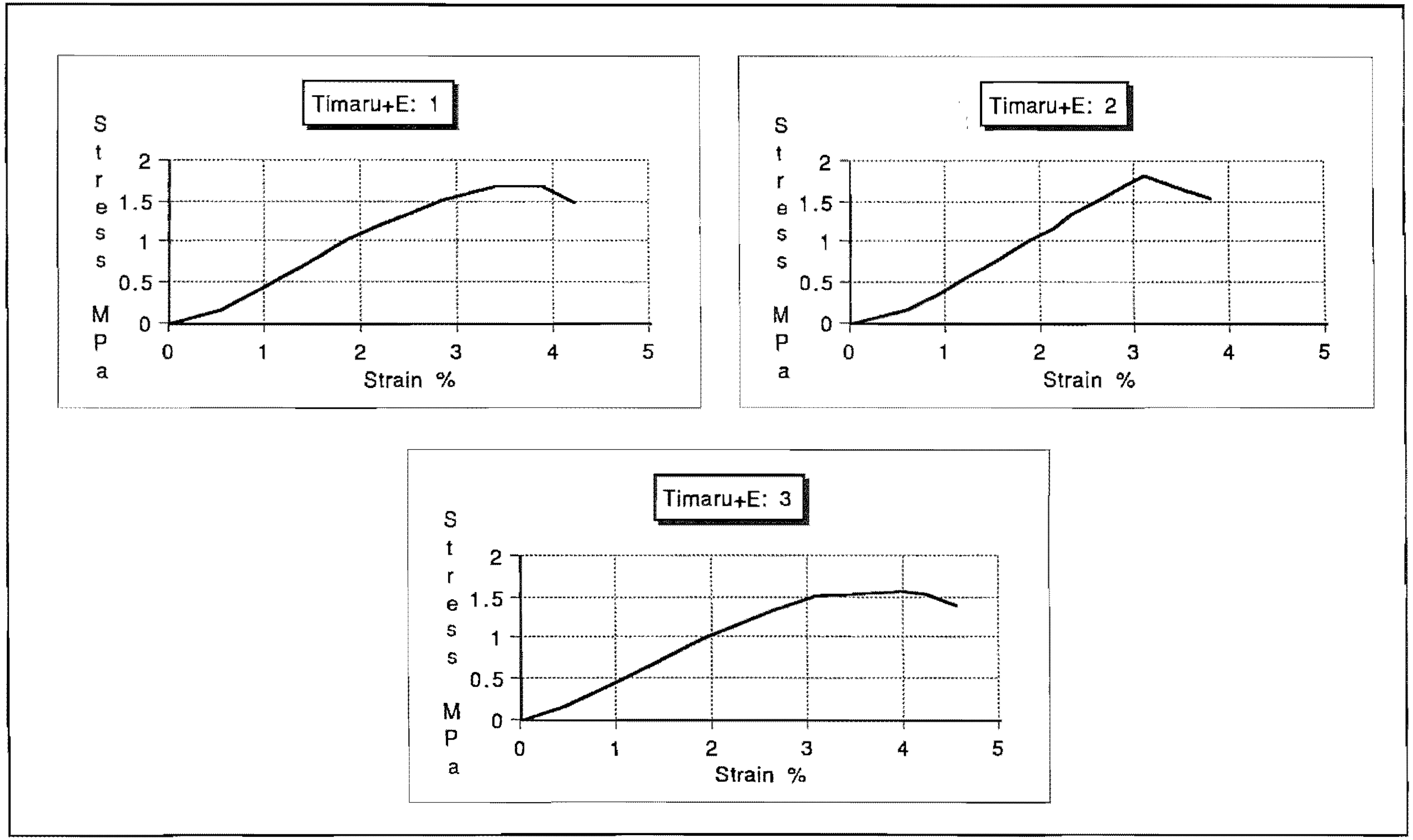


Fig J.18 Stress/Strain relationships from unconfined compressive strength tests carried out on Timaru loess plus Endurazyme applied at a rate of 3 litres/3.5 m^3.

Appendix K: X-ray Diffraction Analysis

K.1 Sample Preparation

1) After grain size analysis (see Appendix D), the sand fraction was retained. Using a small mortar and pestle, a small subsample (about 0.25g) was was ground as finely as possible in approximately 3 ml of ethanol. The slurry was then sucked into a 5 ml pipette. Using the pipette, the slurry was evenly spread over a numbered glass slide. The slide was then left to dry (this usually took only a few minutes). In this way the sand fraction was prepared for XRD analysis

2) After the final eight hour / 9 phi pipette analysis subsample was taken, another 20 ml of 9 phi subsample was also extracted and deposited into a separate beaker. Using a 5 ml pipette, approximately 3 ml of the subsample was spread over a numbered glass slide. The slide was then covered by a beaker and left to dry. The drying process usually took about two days. These mounts are described as being "preferentially orientated" because the clay minerals are allowed to settle with their layering parallel to the slide.

K.2 Apparatus

Clay minerals were identified using a Phillips X-ray diffractometer with CuK gamma radiation sustained by a 1° divergence slit, a 0.2 mm receive slit and a 1°anti scatter slit. A detector is mounted on an arm which pivots around the axis of the instrument. The sample and detector are mechanically combined so that the rotation of the counter through 2Ø° coincides with the rotation of the specimen through Ø°. The crystal structure of the clay minerals is such that the most important diffractions occur within the 2-37° 2Ø scanning distance.

K.3 Treatment Techniques

The samples were initially air dried in a dessicator for 12 hours, and then tested in the diffractomer. The samples were then placed in a solution with a ethlene glycol concentration of 10% and left to saturate for 12 hours. This treatment causes characteristic clay mineral expansion; as a result, any swelling clay minerals may be identified. The samples were then heated at 550 °C for 1 hour. Heating at this high temperature has the effect of destroying the crystal structure of some clay minerals thus allowing them to be differentiated from other clay minerals.

K.4 Data Analysis

K.3.1 Sand Fraction

No attempt was made to estimate the proportion of the different minerals in the sand fraction. However, within each sample it was possible to rank the minerals according to their relative abundance.

K.3.2 Clay Fraction

The X-ray diffraction patterns of the clay mineral fraction are shown in figures K.1-6. These patterns show deflection angles in $2\vartheta°$ and the corresponding mineral layer seperations in Å (10^{-10}m). The The X-ray diffraction patterns were interpreted using Brindley and Brown (1980). The proportions of the different clay minerals were estimated using a semi-quantitative method where a direct comparison is made of the areas under the respective clay mineral peaks. The peak areas were indirectly measured by cutting the peaks out of the sheet and weighing them on a scale accurate to 0.001 g.

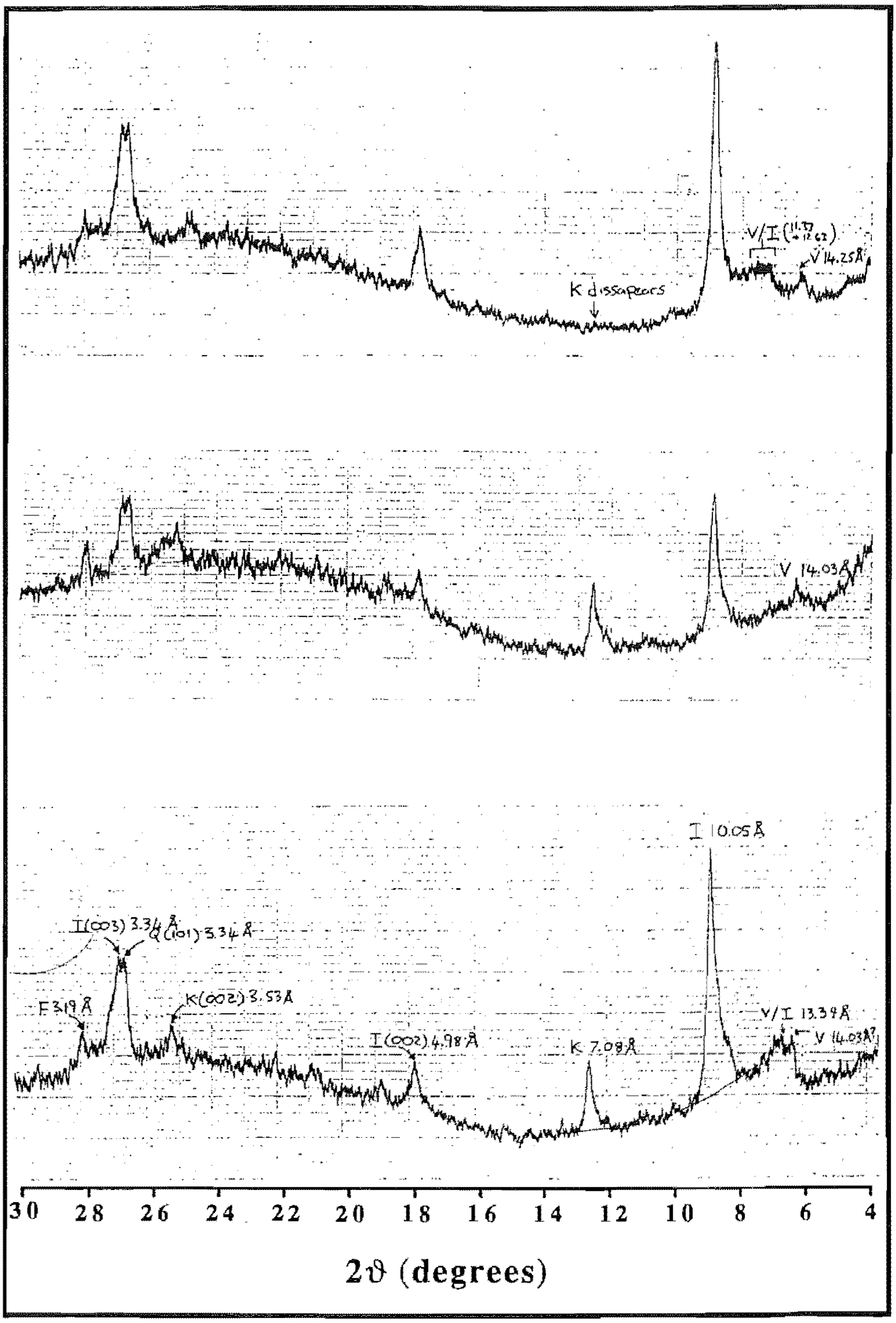


Figure K.1: X-ray diffraction patterns of the clay fraction of loess from the Ahuriri site. The top pattern is the fired mount; the middle pattern is the glycolated mount and the lower pattern is the air dried mount. I = illite, V/I = interstratified vermiculite and illite, K = kaolinite, V = vermiculite, Q = quartz, F = feldspar, UD = undifferentiated.

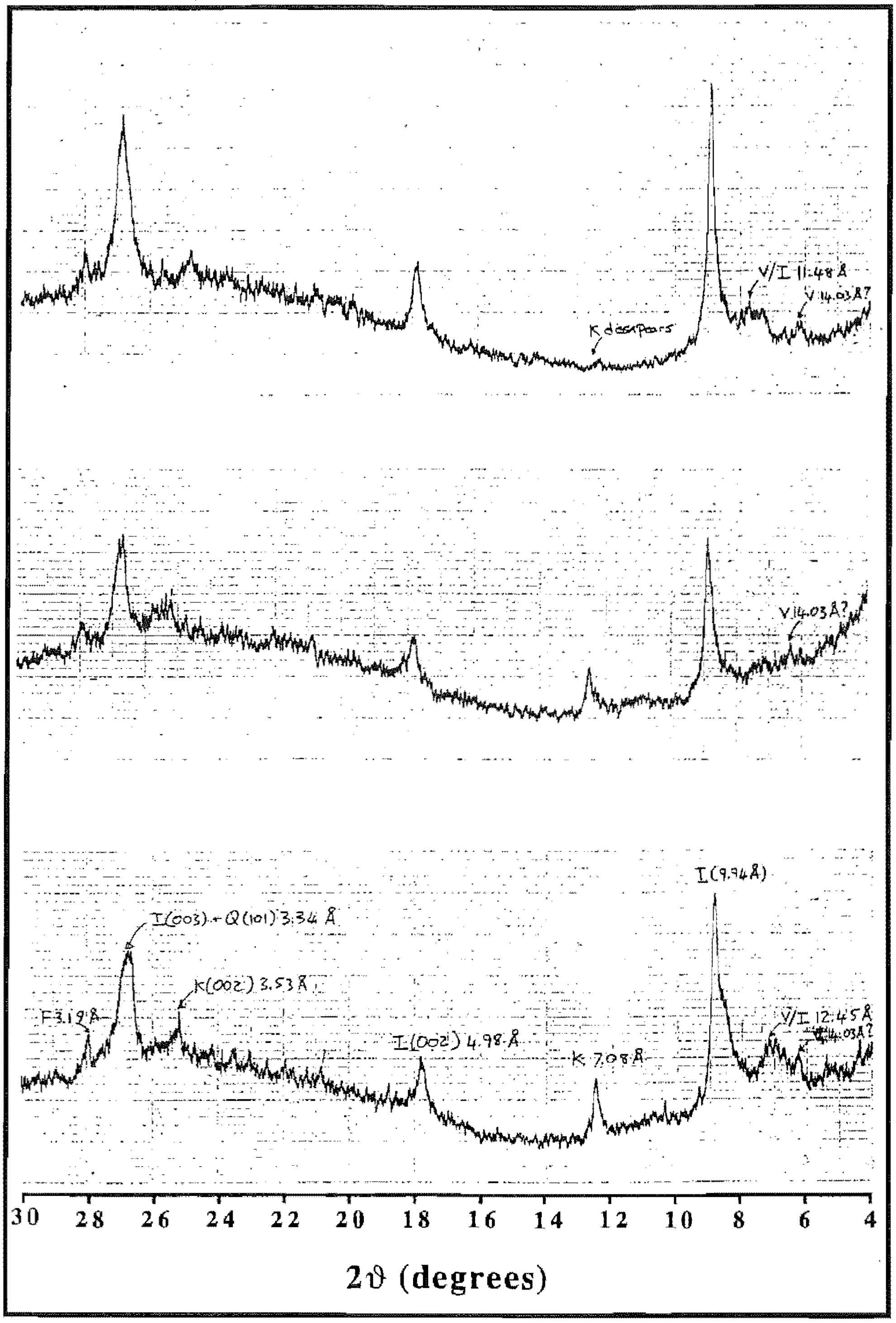


Figure K.2: X-ray diffraction patterns of the clay fraction of loess from the Gebbies valley site. The top pattern is the fired mount; the middle pattern is the glycolated mount and the lower pattern is the air dried mount. I = illite, V/I = interstratified vermiculite and illite, K = kaolinite, V = vermiculite, Q = quartz, F = feldspar, UD = undifferentiated.

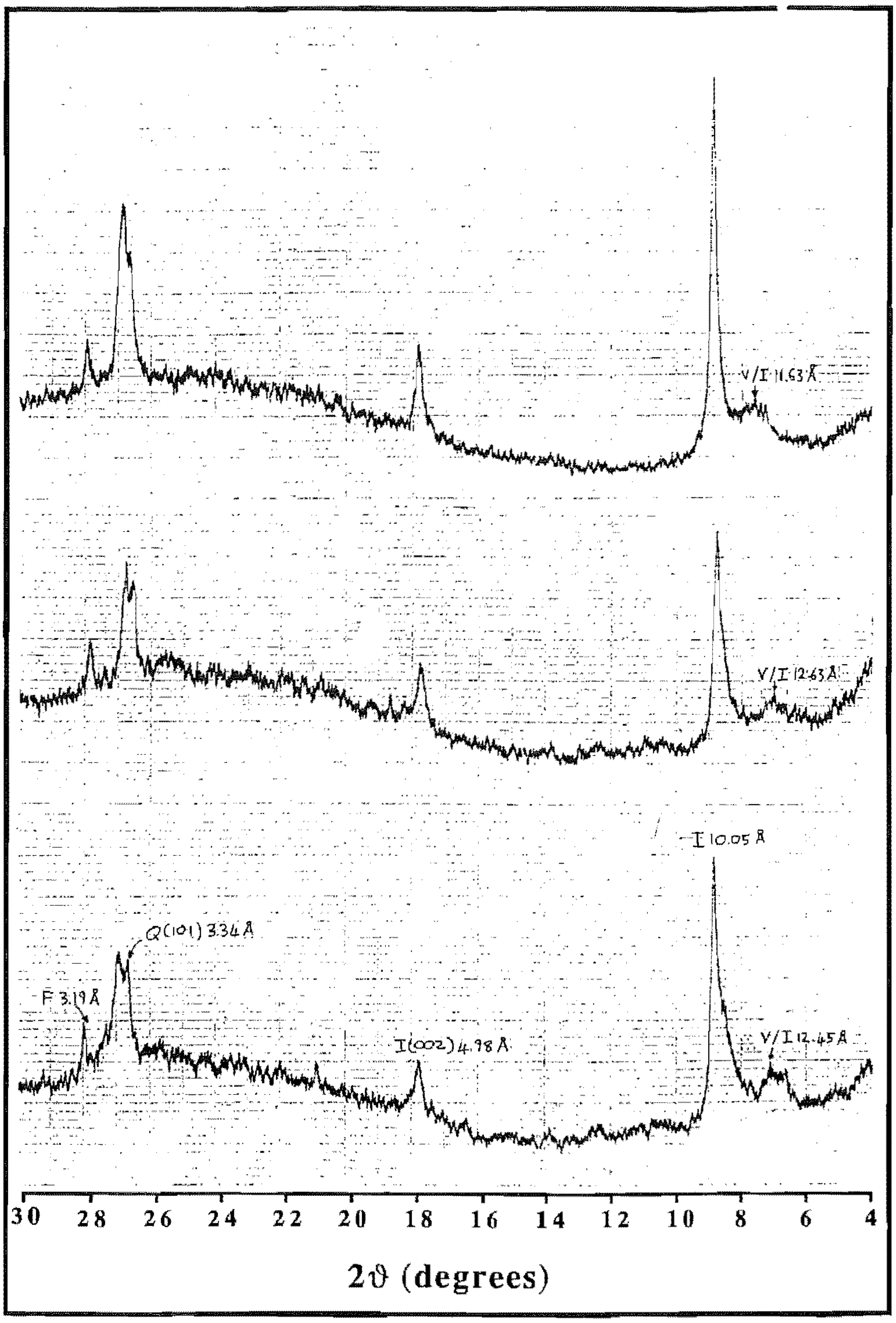


Figure K.3: X-ray diffraction patterns of the clay fraction of loess from the Timaru site. The top pattern is the fired mount; the middle pattern is the glycolated mount and the lower pattern is the air dried mount. I = illite, V/I = interstratified vermiculite and illite, K = kaolinite, V = vermiculite, Q = quartz, F = feldspar, UD = undifferentiated.

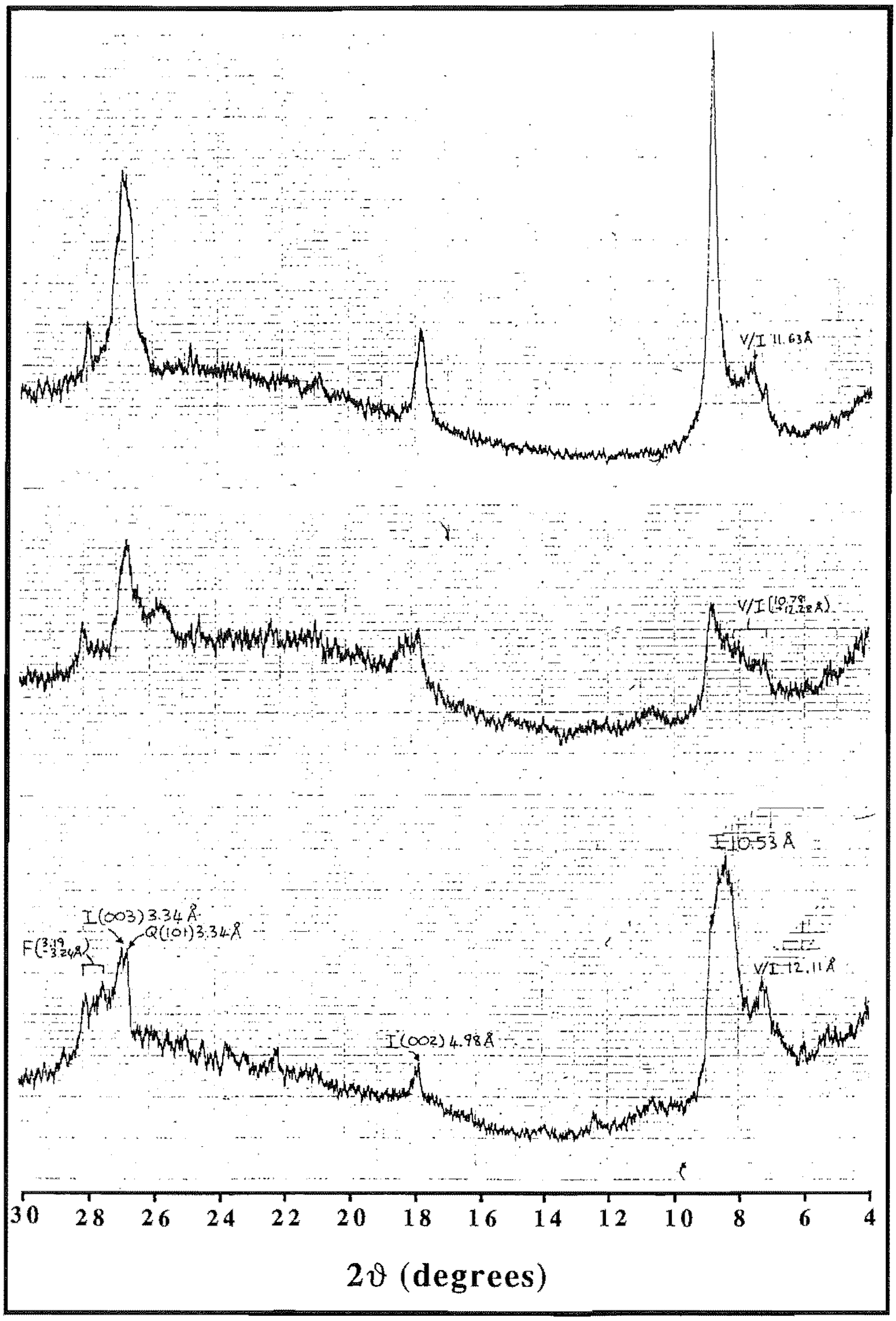


Figure K.4: X-ray diffraction patterns of the clay fraction of loess from the Taiko site. The top pattern is the fired mount; the middle pattern is the glycolated mount and the lower pattern is the air dried mount. I = illite, V/I = interstratified vermiculite and illite, K = kaolinite, V = vermiculite, Q = quartz, F = feldspar, UD = undifferentiated.

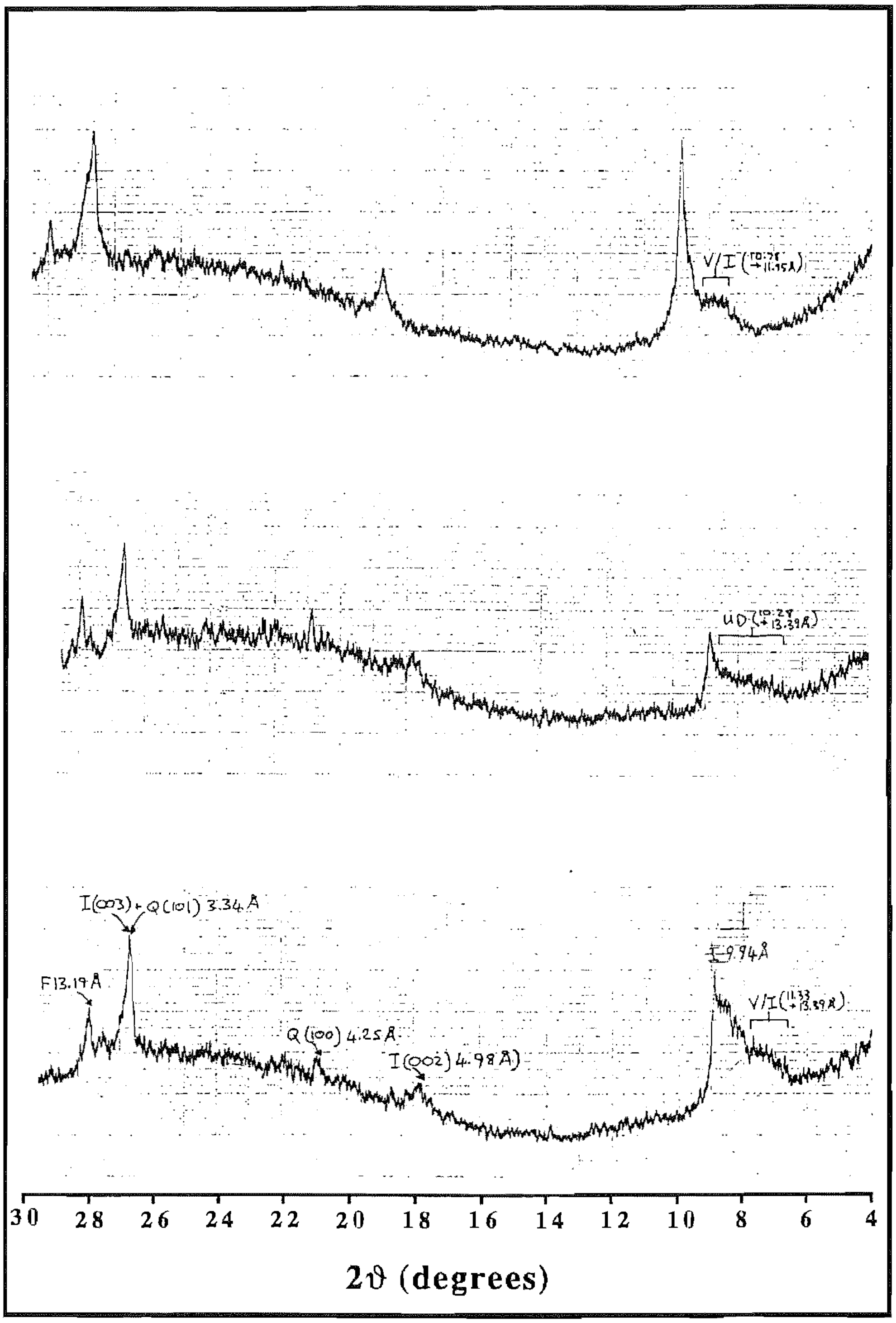


Figure K.5: X-ray diffraction patterns of the clay fraction of loess from the Wither hills site. The top pattern is the fired mount; the middle pattern is the glycolated mount and the lower pattern is the air dried mount. I = illite, V/I = interstratified vermiculite and illite, K = kaolinite, V = vermiculite, Q = quartz, F = feldspar, UD = undifferentiated.

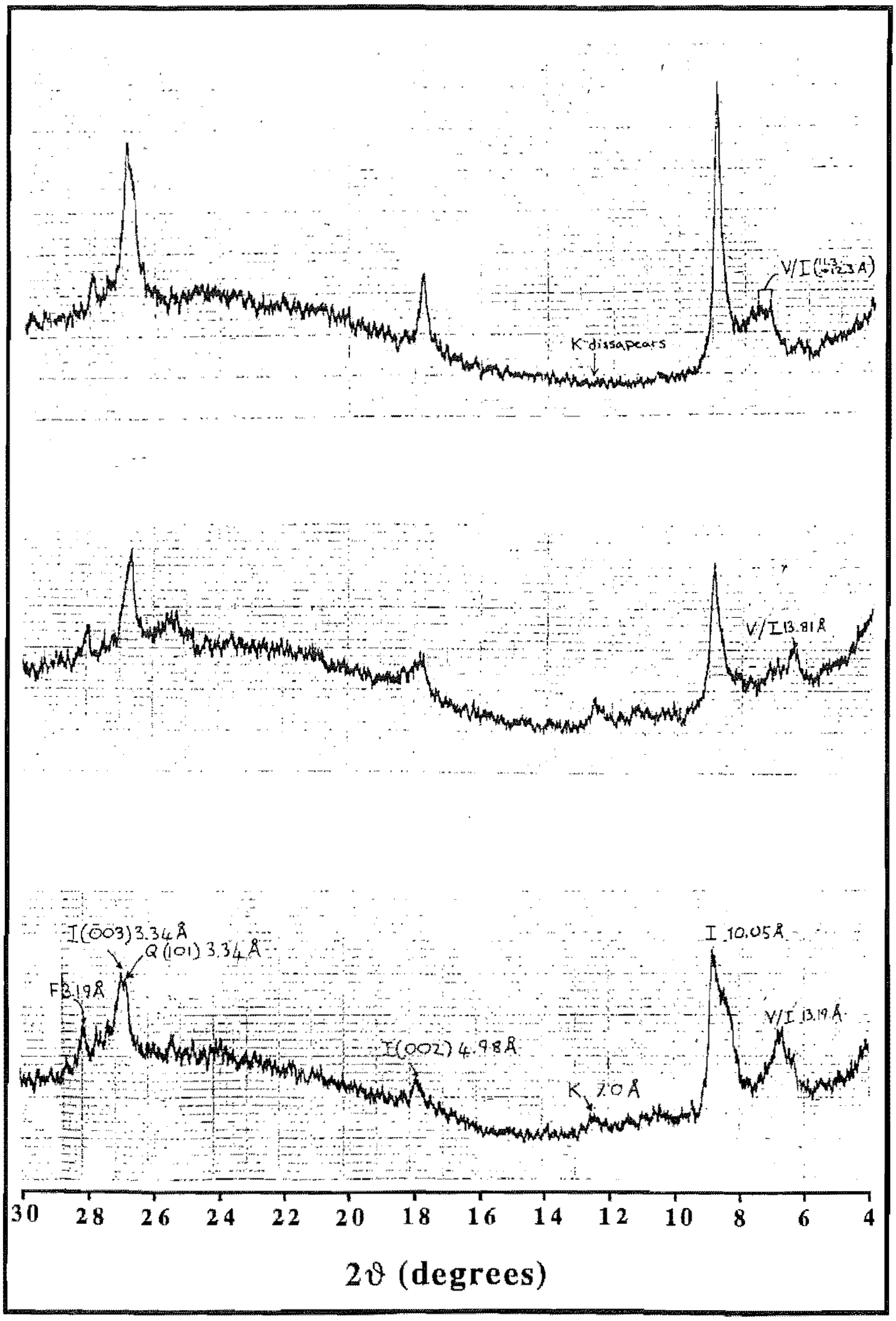


Figure K.6: X-ray diffraction patterns of the clay fraction of loess from the Barrys bay site. The top pattern is the fired mount; the middle pattern is the glycolated mount and the lower pattern is the air dried mount. I = illite, V/I = interstratified vermiculite and illite, K = kaolinite, V = vermiculite, Q = quartz, F = feldspar, UD = undifferentiated.